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Svante Arrhenius (1859–1927)

The legend dies hard that science is a purely objective and logical study in which the personalities of those concerned play no part. Research workers, however, are aware—often painfully so—of the difficulty of getting new ideas accepted, and the history of science offers innumerable examples of the way in which important theories have been established only in the face of bitter and uninformed opposition. Of this, few examples are more striking than that of Svante Arrhenius, the centenary of whose birth falls this year. One of the greatest Swedish men of science, comparable in stature with Linnaeus and Berzelius, his ideas on the nature of solutions of electrolytes were first presented in a thesis that earned him—and that only after much argument among his examiners—a fourth-class doctor's degree in the University of Uppsala, a classification so low that it would not normally have allowed him to become a *docent* there. Yet these ideas, developed but not fundamentally altered, were in time recognized to be of such importance as to make him the third Nobel Laureate in chemistry and director of a famous laboratory created in his honour.

Arrhenius, whose name derives from the fact that his forebears lived in the village of Årena, was born at Wijk on 19th February 1859, the son of an estate manager. The following year the family moved to Uppsala, where Arrhenius went to the cathedral school. At the age of seventeen he entered the University of Uppsala. Academically, his early career there was distinguished, and he passed exceptionally quickly the examinations necessary for him to study for his doctorate. Originally he had intended to work under P. T. Cleve, an expert on the rare earths, but gave up this idea when his interest turned towards theory, in which Cleve was not at all interested. In 1881, therefore, he went to Stockholm to work with E. Edlund, then professor of physics at the Swedish Academy of Sciences. His interest in physics was doubtless stimulated by the fact that the rector of the cathedral school was a good teacher of this subject.

After some preliminary work on spark-gap voltages, he turned his attention to the electrical conductivity of solutions. The properties of solutions were then arousing much interest. Van 't Hoff was developing his revolutionary ideas on the analogy between dissolved substances and gases, Kohlrausch was measuring electrolytic conductivities, and Raoult was devising methods for measuring the molecular weights of solutes. Clausius and Williamson were already speculating on the possibility of dissociation in solution. The theory of solutions was engaging the attention of many able chemists: to Arrhenius fell the honour of crystallizing contemporary thought into an important general theory. The association of his ideas with those of Van 't Hoff was particularly significant, for at almost every point they were complementary.

His first important investigation was directed towards finding a method for determining the molecular weights of non-volatile substances, such as sugar, by measuring the extent by which they lowered the electrical conductivity of salt solutions. The method proved useless, but it led him to a detailed investigation of the conductivity of salt solutions generally. There are two fundamental points that have to be explained by any theory of electrolytes. One is that some electrolytes give relatively strongly conducting solutions, whereas others give much more weakly conducting ones. The other is that for all electrolytes the conducting power is relatively greater the greater the dilution. Arrhenius's ultimate answer to this problem was very simple. He postulated that all electrolytes dissociate in solution into positively and negatively charged ions and—in sharp distinction to earlier workers—that these exist in the solution even when no electric current is passing through it. Strong electrolytes he believed to be largely dissociated into ions (we now regard them as completely dissociated) and weak electrolytes relatively less so. For all electrolytes the degree of dissociation increased with dilution.

As has been noted, the ideas expressed in the thesis for his doctorate at Uppsala, submitted in 1883, almost terminated Arrhenius's academic career. At this stage, however, Arrhenius had by no means perfected the theory with which his name is now associated. He realized that dissolved electrolytes existed partly in an active (conducting) and partly in an inactive form, but he did not define what these might be, nor did he specifically refer to dissociation, although this is implicit in his argument.

Fortunately, Arrhenius was not entirely discouraged by the views of his professors, and he sent copies of his thesis to a number of the leading chemists of the day. Among them was Wilhelm Ostwald, then professor of chemistry at Riga, who

was sufficiently interested to go to Uppsala to discuss the matter with Arrhenius in person. This visit resulted in his getting a junior appointment at Uppsala, doubtless as a result of Ostwald being so impressed by his ability as to offer to get him appointed *docent* at Riga, and this was followed in 1885 by a five-year travelling scholarship from the Swedish Academy of Sciences. This enabled him to travel extensively in Europe and to work with such distinguished men as Van 't Hoff, Ostwald, Boltzmann, and Kohlrausch, all working in the same field. During this time his ideas became clarified and his theory of the ionic dissociation of electrolytes was perfected. The critical year seems to have been 1887. Arrhenius then for the first time saw Van 't Hoff's paper, published in the previous year, in which he expressed the osmotic pressure of solutions in the form $PV=iRT$. Arrhenius quickly identified the i factor as a measure of the dissociation of the solute into ions. Van 't Hoff shared Arrhenius's view, and the two men published their conclusions in 1887 in the first volume of the *Zeitschrift für physikalische Chemie*. Arrhenius related his degree of dissociation α with Van 't Hoff's i factor by the equation

$$i=1+(k-1)\alpha$$

where k is the number of ions into which the molecule of electrolyte dissociates. Ostwald was in agreement, and his great prestige in chemical circles did much to secure recognition for the new theory.

Nevertheless, the theory met with violent opposition in some quarters. Chemical thought at that time was not ready for the idea that in an aqueous solution of common salt, for example, the sodium, which in its ordinary state reacts violently with water, could exist separately from the chlorine. The opposition finally came to a head in 1890. In that year the British Association for the Advancement of Science, meeting at Leeds, held a discussion 'On Theories of Solution', to which the three were invited. Ostwald and Van 't Hoff went to argue in person, and Arrhenius sent a paper. The orthodox view was forcibly put by such men as S. U. Pickering, J. H. Gladstone, and G. F. Fitzgerald, but by the end of the meeting there was no doubt that the new ideas prevailed. With the vindication of his theory, Arrhenius's affairs took a turn for the better, although to his disappointment he was still largely ignored in his own country, to which he was deeply attached. The chair of chemistry at Giessen was offered to him in 1891, but he preferred a lectureship in the technical university in Stockholm. This was converted into a professorship in 1895, but Arrhenius was appointed to it only after much opposition and in the absence of any other suitable candidate. A year later, however, he became Rector. In 1902 he was awarded the Davy Medal of the Royal Society and in 1903 the Nobel Prize for chemistry.

In 1905 the prospect of Arrhenius's leaving Sweden to join Van 't Hoff in Germany led the Swedish Academy of Sciences to found a Nobel Institute for Physical Chemistry. This was in place of two separate institutes that had been planned, one for chemistry and one for physics, and the decision is a measure of the extent to which he had united these two important fields of science. In 1909 Arrhenius, at the age of fifty, began to work there as director and continued almost until his death in 1927.

His later researches covered a wide range: from cosmic physics to glaciology, from immunochemistry to viscosity. In these investigations he was much helped by his wide knowledge, remarkable memory, and ability to see a connection between apparently unrelated facts. In addition, he was a gifted linguist and thus could particularly easily exchange views with colleagues in other countries. Nevertheless, he recognized that this was a fortunate gift not widely bestowed, and he advocated the use of a universal language based on English. He was a well-known expositor of science and author of many popular scientific books which were widely translated.

His later work was by no means unimportant, but it is for the development of the theory of solutions that Arrhenius is most deserving of lasting fame. Apart from the intrinsic importance of his discoveries—their significance in the chemical industry, for example, needs no emphasis—the story of his career forcibly demonstrates that while new ideas demand most searching criticism before they are accepted it is important for this to be objective. This, it may be remarked, is a lesson that not only scientists would do well to learn.

Lightning

D. J. MALAN

Lightning was studied systematically as early as the eighteenth century, but it was impossible to understand the processes involved until recently, when high-speed cameras and cathode-ray oscillographs became available. The apparatus, and some of the results obtained with it, are discussed in this review of the most important aspects of thunderstorm electricity.

The first systematic investigation of thunderstorm electricity dates from the middle of the eighteenth century, when Benjamin Franklin proved that lightning was an electric spark and that negative electricity was usually involved in a discharge to ground. Although Franklin's experiments were repeated and confirmed, there was no significant advance in the knowledge of lightning until the present century, because a lightning discharge consists of a series of very rapid processes and further progress had to await the development of new experimental techniques. Only such methods as high-speed photography and cathode-ray oscillography could give the high time-resolution required.

The classic work of C. T. R. Wilson and his school from 1916 onwards initiated a new era of discovery in the field of thunderstorm electricity. Appleton, Watson-Watt, and Herd in England, and Norinder in Sweden, were the first to use cathode-ray oscillographs for the study of the fast components of the electrical field changes due to lightning discharges. In the meantime C. V. Boys [1] had invented an ingenious high-speed camera which was used with remarkable success in South Africa by B. F. J. Schonland and his collaborators, who obtained important information on the mechanism of the electrical breakdown in the lightning spark.

The initial discoveries awakened new and world-wide interest in research on lightning and on related problems such as the propagation of atmospherics, radiogoniometry for locating distant thunderstorms, the protection of aircraft and electrical power lines against damage by lightning, and the meteorology of thunderclouds. These and other studies are still continuing, apparatus and techniques have been improved, and the invention of radar gave research workers a powerful new tool for investigating the interiors of thunderclouds.

The erratic occurrence of thunderstorms limits the opportunities for observation, and direct approach by laboratory experiments can be only partly successful as it is impossible to simulate on a small scale the conditions prevailing in large thunderclouds. It might appear that observations made from aircraft could supply a great deal of information about discharges inside thunderclouds. However, lightning is a transient phenomenon, so that the chance that an aircraft, flying at high speed, will traverse the interesting region of the cloud at the right moment is rather remote, and even if it does do so only a relatively small volume of the total region involved in the discharge could be sampled. Aircraft observations have, nevertheless, supplied valuable information about air currents, temperatures, and the distribution of solid and liquid phases of water in various parts of a thundercloud. This information is essential for discovering the process, or combination of processes, by which electricity is generated in the cloud.

There are three main types of lightning discharges: flashes to ground, air discharges, and cloud flashes. Flashes to ground are discharges between a cloud and the ground. They show profuse branching in a downward direction. The altitude of the cloud base lies between 1 and 2 kilometres, but the total length of the visible track of a flash to ground will be greater owing to the tortuous path of the flash. Air discharges are flashes that issue from the cloud and instead of reaching the ground end in space charges in the air. Sometimes air discharges running horizontally below the base of the cloud are as much as 10 miles in length. Cloud flashes, popularly known as sheet lightning, are discharges between charged centres inside the cloud. These discharges cause diffuse illumination of the cloud, and their discharge channels are rarely visible.

Recent investigations by radar have revealed that discharges inside long banks of clouds often extend for 30 and occasionally even for 100 miles [2]. In this type of cloud flash the illumination is seen to start at one end of a long bank of clouds and to travel towards the other. It was formerly

thought that completely separate and isolated charge centres or cells in the cloud were discharged in succession by the trigger action of the photo-electric and electrostatic effects of the preceding discharge, but radar observations have shown that the discharge is in fact continuous.

HIGH-SPEED PHOTOGRAPHY

Hoffert in 1890 and Walter in 1903 used the simple expedient of rocking an ordinary camera to and fro about a vertical axis to study the structure of lightning flashes. They were able to show that a flash to ground usually consists of a series of discharges following each other at intervals along the same track, and they were also able to detect a pre-discharge before the first stroke. Such apparatus could give only qualitative results. The Boys camera, which represents a very considerable refinement of this idea, has played such an important role in the study of lightning that a short description of it will be given before discussing the results obtained.

Figure 3 shows the combination of cameras used in South Africa by B. F. J. Schonland, D. J. Malan, and H. Collens [3]. The large camera in the centre is the Boys camera. It has two lenses, mounted diametrically opposite each other on a circular disk that is rotated at high speed by a belt drive when the large pulley at the left is turned.

Let us consider what happens when a lightning discharge that starts at the cloud and progresses vertically downwards to ground is photographed. At any instant the lenses of the Boys camera are moving in opposite directions. Thus if the lenses are horizontally opposite each other at the moment when the discharge starts, one lens will be moving downwards and the other upwards. The lens moving downwards, in the direction of advance of the discharge, lengthens the photographic image by an amount equal to the distance moved by the lens during the time the discharge has taken to proceed to the ground. Conversely, the other lens shortens the image by the same amount. The time taken by the discharge to reach the ground can thus be obtained by dividing the difference between the lengths of the images by twice the linear speed of the lenses.

If the lenses are in any other position when the discharge starts, one lens will be moving towards the right and the other towards the left, so that the images of the advancing tip of the lightning discharge will be distorted towards the right and the left respectively. By measuring these distortions it is possible to draw up a timetable of the progress of the lightning flash and to determine in which direction it was going. The lenses of the camera shown in figure 3 are rotated at 50 revolutions per second, making it possible to measure intervals with an accuracy of a few microseconds.

The cameras are usually operated at night so that the lens shutters can remain open while waiting for a flash. Photographs can also be taken in daylight by using the disturbance produced on a radio receiver at the commencement of the lightning flash to operate a relay that opens the camera shutter for a pre-set time. Other cameras have been designed to obtain linear, instead of circular, motion of the lens relative to the film, because the results are then easier to interpret. These have been very useful for studying the slow components of lightning flashes.

When the lightning flash has several consecutive strokes, the lenses of a Boys camera will make more than one revolution during the course of the discharge, so that it is not possible to pick out on the photograph the order of sequence of the strokes. The small camera seen at the top of figure 3 is used to overcome this difficulty. It is similar in construction to the main Boys camera but has only one lens on its disk, which is slowed down, by intermediate belts and pulleys, so as to turn at one revolution per second. As most lightning flashes last for less than a second the images of successive strokes will follow each other in chronological order without overlap. Knowing the speed ratio of the cameras, it is easy to correlate the strokes photographed by the fast camera with those of the slow one. The third camera, appearing at the right in figure 3, is an ordinary camera which is used for obtaining a still picture of the flash. Figure 2 (*a*, *b*) shows a set of photographs taken respectively with the slow and fast cameras of figure 3 of a lightning flash that had seven component strokes following each other in the order 1–7.

RESULTS OF PHOTOGRAPHIC STUDIES

As already stated, flashes to ground may consist of several successive strokes following the same track. At Johannesburg 50 per cent of all flashes have more than four strokes, and flashes having twenty strokes are not uncommon. In England, by contrast, the majority of flashes have only one stroke [4], the difference being evidently due to the greater activity of tropical thunderstorms. Usually only the first stroke has branches (figure 2, stroke 1). The most frequent time interval between strokes is from 30 to 50 milliseconds.

Each stroke is dual in nature. A faintly luminous discharge, called a leader streamer, issues first from the base of the cloud and proceeds downwards. When it arrives near the ground it is met by a very bright and intense discharge called a return stroke, which sparks over from the ground and travels upwards at high speed along the previously formed leader channel.

The first leader initiates the electrical breakdown between the base of the cloud and the ground and therefore has no prepared track through the air. High-speed photographs show that it advances rapidly for a distance of about 20 metres and then seems to pause. After an interval of about 50 microseconds it suddenly surges ahead a further 20 metres as a relatively bright discharge and pauses again. The intermittent step-like advances are repeated until the leader finally reaches the ground, when the bright return stroke follows. The figures quoted are mean values [3].

Figure 4 shows a Boys camera photograph of such a stepped leader. The lens rotation is from right to left, and the leader steps can be seen to the right of the return stroke, the image of which is considerably widened because its luminosity lasts much longer than that of the leader steps. The diameter of the return-stroke channel is actually very much less than that of the stepped leader, owing to the magnetic pinch effect of its heavy current [13].

The fact that the overall velocity of advance of a stepped leader is remarkably constant suggests that the bright steps are preceded by a faint pilot streamer which advances continuously during the apparently quiescent intervals. When such a pilot streamer has forged ahead a few tens of metres it demands a heavier current, with the result that its luminosity suddenly increases and it appears as a bright step. The presence of this faint pilot streamer advancing at about 2×10^7 cm/sec has been deduced from theoretical reasoning, but it has not yet been demonstrated photographically with complete success.

The discovery of the stepped leader constituted a great advance in understanding how it was possible for a lightning spark to jump the mile-long gap between the cloud and the ground. The total potential is of the order of 100 million volts, and the overall potential gradient is thus only a small fraction of that required for spark breakdown between metal electrodes in the laboratory.

Several theories have been advanced to explain the mechanism of the bright step, notably by B. F. J. Schonland [5] and C. E. R. Bruce [6]. Although they differ somewhat in detail they lead to the same overall conclusion. At the completion of a step a highly conducting path exists between the cloud and the leading tip of the step, so that the potential here is of the same order of magnitude as the cloud potential. The resulting concentration of lines of force at the leader tip makes it possible for a faint pilot streamer to advance a limited distance. However, the intense step discharge that then follows re-establishes a high tip potential, so that the pilot streamer can forge ahead on its next stage. There is no reason why such a step-like discharge, once started, should not go on indefinitely, provided the cloud can supply the necessary charge. This conclusion is supported by the existence of extremely long horizontal air discharges which, as camera studies have shown, advance in stepped-leader fashion.

During the advance of the stepped leader, negative charge is being lowered from the cloud. The pilot streamer on its way to ground forms side branches to concentrations of positive space charge in the air that have originated from point discharge at the ground. The ground, a good conductor, acquires an induced positive charge under the advancing negatively charged leader. When the leader reaches the ground the negative charge distributed along its channel will be neutralized by the return stroke, which can be considered as positive charge moving upwards along the channel and outwards along the branches previously formed by the leader. The luminosity of the return stroke travels upwards at speeds varying from a tenth to a third of the velocity of light.

Figure 1 shows the timetable in microseconds of the progress of a return stroke. Whereas the luminosity takes 71 microseconds to reach the cloud it reaches the lower end of the long branch at the right only after 327 microseconds.

The intense current, of about 30 000 amperes, in the first return stroke causes heavy ionization of the lightning channel, which remains conductive for about 100 milliseconds after the current has stopped flowing. If a second stroke follows within this time interval it thus encounters a prepared path of low resistance along which its leader advances rapidly and continuously in the form of a bright dart, going directly to ground along the original main channel without branching. This dart leader also distributes negative charge along its track and is consequently followed by an intense upward-moving return stroke from the ground; this is similar to the first return stroke but without its branches.

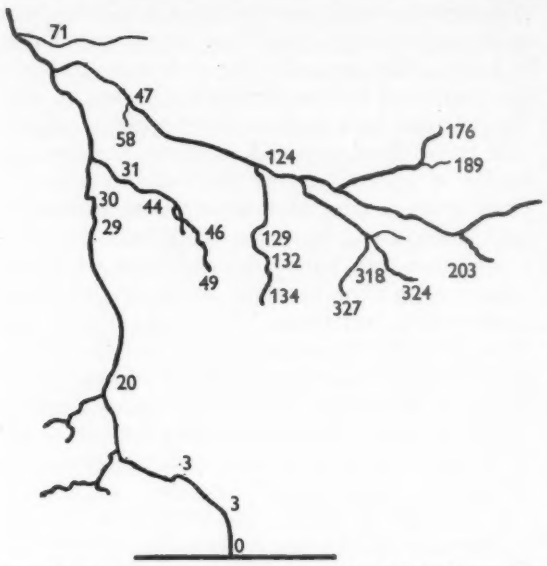

FIGURE 1 – *Timetable in microseconds of the advance of a return stroke towards the cloud and along the branches.*

Other subsequent strokes will also have dart leaders, whose velocities are approximately ten times that of stepped leaders. Figure 5 shows a dart leader at the right and the following return stroke at the left, the motion of the camera lens being from right to left. If the interval that has elapsed since the previous return stroke approaches 100 milliseconds, the ionization remaining in the upper part of the channel is barely sufficient to guide the leader, which then again becomes step-like in nature, the step lengths and intervals being short. By the time the leader reaches it, the lower part of the channel has generally lost its ionization to such an extent that it has no guiding effect at all. The leader then immediately becomes a true stepped leader and follows an independent path in its further advance, and strikes the ground at a different spot from the previous strokes.

THE MAIN CHARGE CENTRES OF THUNDERCLOUDS

By convention, the electric field at the ground caused by a charge in a cloud is considered to be positive when the charge is positive, and negative when the charge is negative. In the case of actual thunderclouds the field is found to be negative when the cloud is near and positive when it is more distant. This effect can be ascribed to the presence of two charged regions one above the other and of opposite polarity, the lower or N region being negatively charged and the upper or P region being positively charged.

A lightning discharge causes a sudden change in electric field. With rare exceptions, flashes to ground always give positive field changes, indicating that the cloud has become less negatively charged and that flashes to ground thus tap the negative or N charge centre and bring negative electricity to earth. Cloud flashes, on the other hand, give positive field changes when the cloud is near the observer and negative field changes when it is distant, from which observation it is concluded that cloud flashes are discharges between the N and the P charge centres. Apart from showing that the positively charged region is higher than the negatively charged region, these general observations give no indication of the actual heights at which these regions are situated.

The change in electric field due to a lightning flash as measured at an observation post on the ground depends on the distance (D) of the flash, the magnitude (Q) of the charge brought to earth or neutralized in the cloud, and the initial height (H) of the charge. D can be found by timing the interval between seeing the lightning and hearing the thunder. It is obvious that the two unknown quantities Q and H cannot be determined from a single observation, but that two independent measurements of the field changes at different distances are required. In the case of cloud flashes between charges at different heights at least three measurements are necessary.

The technique of using a network of observing stations has been tried, but the results have been rather disappointing because the theoretical calculations are based on an assumed spherical distribution of the cloud charges, whereas, as will be shown later, this is far from being so.

DISTRIBUTION OF THE CHARGES

The first direct determination of the heights of the various thundercloud charges is due to G. C. Simpson, F. J. Scrase, and G. D. Robinson [7], who sent up sounding balloons carrying an ingenious apparatus, which they called an alti-electrograph, for measuring electric fields. The apparatus consists essentially of a long trailing wire in which a break is made near its top end; the severed ends are connected to electrodes pressing on pole-finding paper. Strong fields cause an electric current to pass between the ends of the wire, and either the upper or the lower electrode will colour the paper, depending on the direction of the field. The paper is moved by a clockwork motor, and the width of the coloured

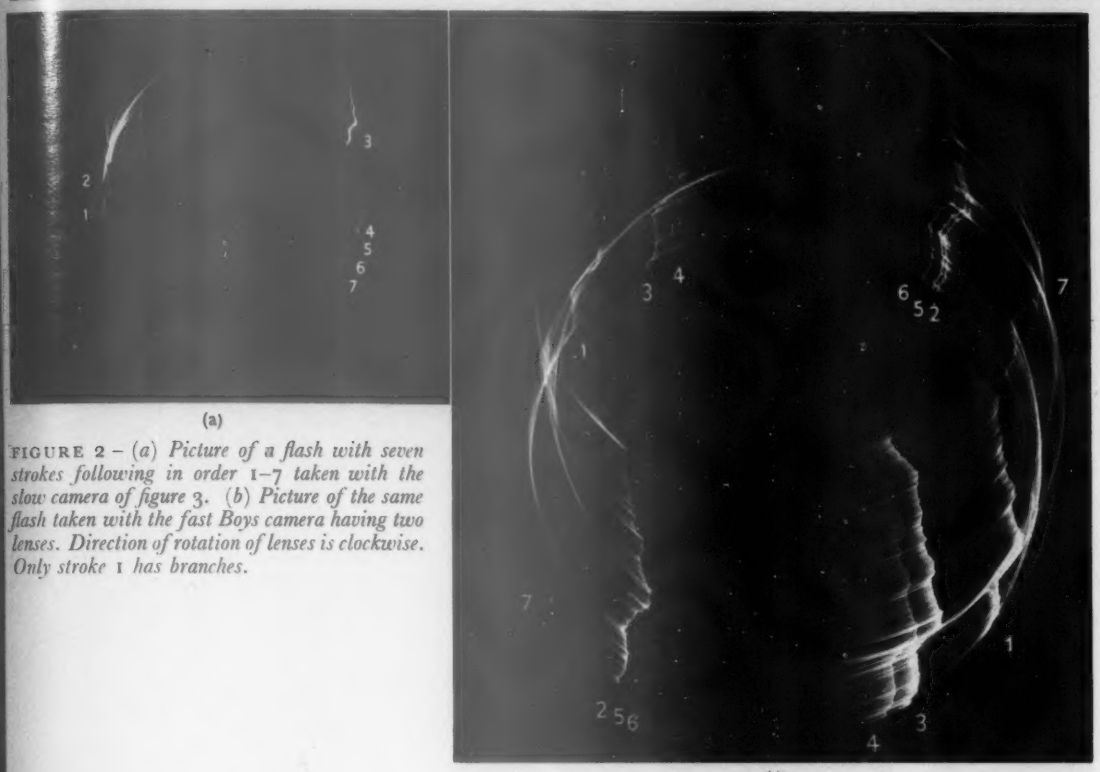

FIGURE 2 – (*a*) *Picture of a flash with seven strokes following in order* 1–7 *taken with the slow camera of figure* 3. (*b*) *Picture of the same flash taken with the fast Boys camera having two lenses. Direction of rotation of lenses is clockwise. Only stroke* 1 *has branches.*

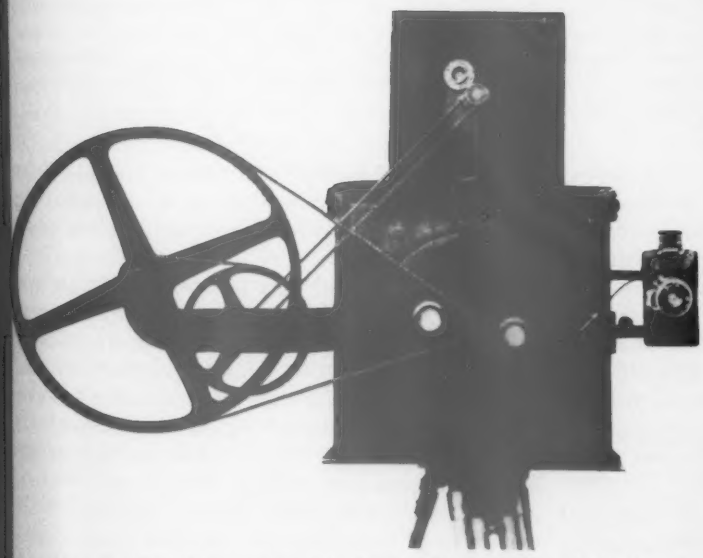

FIGURE 3 – *Set of cameras used in South Africa. Bottom, double-lens fast Boys camera; top, single-lens slow-speed camera; right, still camera.*

trace serves as a measure of the field strength.

These balloon soundings showed that the negative charge centre is situated above the base of the cloud, in a region where the temperature is below o° C, and that the main positive charge centre is higher up, towards the top of the cloud. These workers also made the important discovery that another small positive charge is often present in the base of the cloud, where the temperature is above o° C.

The presence of this lower positive (*p*) charge accounts for the fact that the electric field just before the occurrence of a flash to ground near by is very often found to be quite small or even positive in sign; the small positive charge immediately overhead counteracts the effect of the much larger negative charge higher up. Lightning

FIGURE 4 – *Stepped leader. Lens motion is from right to left. The step-by-step downward advance of the leader can be seen on the right. The image of the bright return stroke at the left is broadened owing to its continuing luminosity. The horizontal streaks at the left are caused by the uneven fading out of the luminosity due to bends in the channel.*

FIGURE 5 – *Dart leader. Lens motion is from right to left. The leader starting at the top right proceeds to ground, where it is followed by the return stroke at the left. The motion of the lens distorts the images and gives the V-shaped picture.*

alarms designed to ring a bell or flash a light when the field is high are thus liable to fail in their prediction when a very near discharge is imminent.

Sounding balloons suffer from the disadvantage that their path of flight cannot be controlled and that the time they take to traverse the cloud is long compared with the duration of the electrical processes. The results obtained are therefore difficult to interpret. For these reasons a different method of investigating the charge distribution was subsequently used in South Africa [8]. It was there shown that it was possible to calculate how the main negative charge is distributed in thunderclouds by examining at ground level the variation with distance of either the electrostatic field changes due to the leader process, or the relative amplitudes of leader and return stroke field changes, or the slow field changes taking place during the intervals between the successive strokes of a flash to ground.

These methods of investigation led to the unexpected discovery that the negative charge is distributed in an approximately vertical column extending from about 3·5 km to 8·5 km altitude. It was found also that the first stroke of a flash to ground tapped a limited region of charge at an altitude of about 3·5 km and that the succeeding strokes tapped progressively higher and higher regions of the negatively charged column. This was a surprising discovery, because it was previously thought that successive strokes tapped completely separate and isolated regions of charge

distributed horizontally near the base of the cloud.

The whole negative column is in a region of sub-zero temperature, its top often reaching to the −40° C level (figure 6). This temperature has a special significance, because it is the lowest temperature to which a droplet of pure water can be supercooled without freezing. It follows that only ice particles are present above the −40° C level, while both ice particles and water drops can exist in the region of the negative column, a fact which must have some bearing on the physical processes involved in the electrification of the cloud.

The distribution of the electrical charges involved in lightning discharges can also be studied by radar, because the charges in the cloud are tapped by a multitude of discharge streamers which create highly ionized regions from which radar pulses can be reflected. Recent radar studies [9] have confirmed the presence of a high column of negative charge and have further shown that its diameter is about one or two kilometres.

The negative column is associated with a cell or chimney of strong upward air currents in the cloud. Large particles of ice or water which are negatively charged tend to fall downwards under gravity, while smaller particles which are positively charged are blown upwards to form the upper positive charge, as will be explained later. It is likely that some of the light positive particles spill over the top of the chimney of updraught and are carried to lower altitudes by the downdraughts existing towards the rear of a fully developed thundercloud. This conclusion is confirmed by radar observations, which show that discharges inside the cloud between the *N* and *P* charge centres very often fail to reach the same altitude as the final strokes of flashes to ground, showing that all the *P* charge is not wholly above the negative column.

Figure 6 illustrates the probable distribution of the charges in a thundercloud cell, taking into account all the information available at present. A large thundercloud may contain several active cells. At Johannesburg, which lies on a plateau 1800 metres above mean sea level, the tops of thunderclouds reach altitudes of 12 000 metres above ground level. In more temperate latitudes the clouds generally do not reach such a great height, so that the negative column may possibly be somewhat shorter in vertical extent.

ELECTRICAL BREAKDOWN PROCESSES IN THE CLOUD

The electrically charged regions of a thundercloud contain numbers of water drops and ice particles which carry charges but are insulated from each other by the intervening air. Such a region cannot be discharged before electrical contact is established between the individual charged particles so as to collect and converge their charges into a conducting ionized channel that can then forge ahead as a lightning flash. The following explanation of the mechanism by which such a conducting channel is formed in the case of a flash to ground was first suggested by L. B. Loeb [10] from theoretical reasoning. His predictions were subsequently confirmed by the experimental work of N. D. Clarence and D. J. Malan [11].

The region between the bottom of the negative column *N* and the lower positive charge *p* (figure 6) in the base of the cloud contains large water drops in a growing electric field. A positive charge is induced on the upper and a negative charge on the lower surface of each drop, which becomes elongated on account of the opposing electrical attractions of the *N* and the *p* cloud charges.

As the charges in the cloud build up, the field increases and the drops get longer and longer until the field reaches a value of 10^4 volts/cm. At this stage a drop becomes unstable and a long water

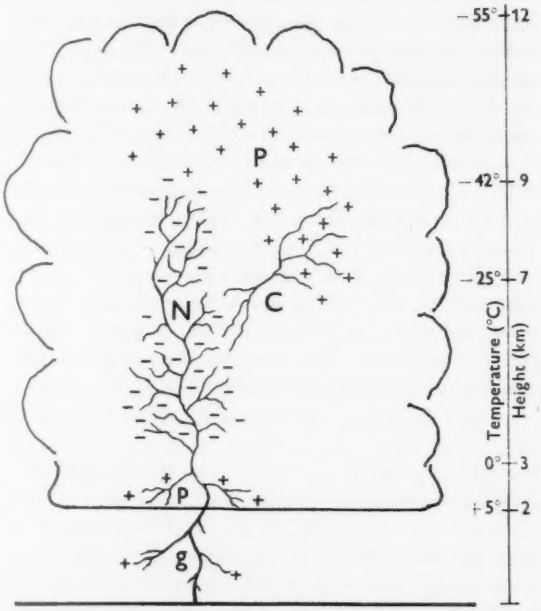

FIGURE 6 – *Probable distribution of the main charges in a thundercloud at Johannesburg, altitude* 6000 *ft above mean sea level.* P, *upper positive charge;* N, *negative column;* p, *lower positive charge;* g, *flash to ground which taps the negative column in stages from its base upwards;* C, *cloud flash between the* N *and* P *regions.*

filament shoots out from its positive end; a glow discharge starts at the fine tip of this filament, which then breaks up, leaving a spray of minute charged droplets and ions. The drop will continue shooting off filaments until its diameter is reduced to 1 mm [12]. It needs only one propitiously placed drop in the cloud to initiate spraying, which then spreads from drop to drop in a chain reaction until a conducting channel is established between the N and the p charge centres. This completes the first stage of the electrical breakdown process.

Neutralization of the p charge now follows, after which the conducting channel extending to the base of the cloud becomes negatively charged, the negative charge being supplied by streamers radiating into and tapping the negative column. As charging continues, the electric field in front of the lower tip of the conducting channel keeps on rising until it reaches 6×10^4 volts/cm, which is the field required [5] for starting off the pilot streamer and stepped leader breakdown through the air towards the ground.

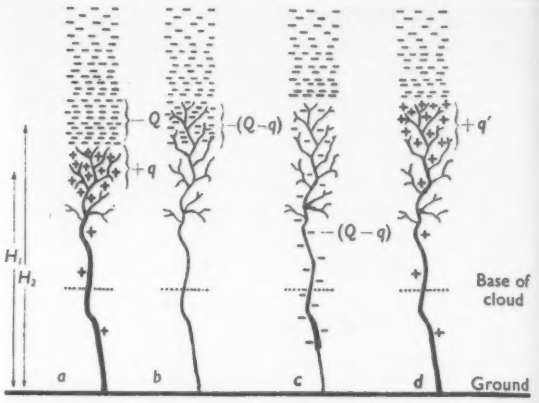

FIGURE 7 – *Diagram showing the electrical processes taking place in the cloud during the interval between two successive strokes of a flash to ground.*

THE REASON FOR MULTIPLE STROKES

The charge distribution in the negative column is continuous but not of uniform density. It would have been expected that such a column of charge should discharge continuously once the leader has established electrical contact with the ground, and not intermittently in a series of strokes as usually happens. The answer to this perplexing riddle was found by examining the slow electrostatic field changes occurring in the intervals between the successive strokes of a flash to ground [8]. These junction, or J, field changes, as they are called, showed that positive charge was moving upwards at the rate of 3×10^6 cm/sec and being neutralized in the process. The stages of the J process occurring between two successive strokes of a flash to ground are illustrated in figures 7(*a*, *b*).

Figure 7*a* shows the distribution of charges at the completion of a return stroke which has brought a positive charge $+q$ to the highly conducting branched streamers at the top of the channel at a mean height H_1. In the strong field between $+q$ and $-Q$ positive streamers start penetrating into $-Q$ until the positive charge $+q$ has been neutralized, leaving a residual negative charge $-(Q-q)$ in a region which has been made conducting by the streamers at a mean height H_2, shown at *b*.

This negative charge now flows down the channel as a dart leader as shown at *c*. The return stroke which follows again brings a positive charge to the top of the channel as shown at *d*. Conditions are now similar to those at *a*. The whole J process is successively repeated, draining higher and higher regions of the negative column until its charge is exhausted. Investigations by means of radar [9] have shown that in addition to the J processes at the top of the channel, illustrated in figure 7, the mopping up of residual negative charges lower down in the cloud continues throughout the flash.

Since flashes which have only one or two strokes are often followed by a continuous current to ground of 50–80 amperes lasting for a few hundred milliseconds, it has been suggested that in these cases the negative column is drained in a continuous fashion because the density of its charge distribution is exceptionally high, due to as yet unknown meteorological factors. This type of flash is more likely to ignite an inflammable structure or to set fire to a forest than the intermittent type of flash, each stroke of which passes a much heavier current, of explosive violence, but lasts only for some microseconds.

ELECTRIFICATION PROCESSES

Until about twelve years ago it was thought that the falling drop electrification theory of C. T. R. Wilson could account for the separation of the main positive and negative charges in a thundercloud. According to this theory a large water drop in a cloud will have an induced positive charge on its lower surface and a negative charge on its upper surface, due to the normal electric field. The drop is supported, or slowly falls, in a strong upward air current, the air

normally containing approximately equal numbers of negative and positive ions. When a negative ion is blown towards the drop it will be attracted by the spatially lower positive charge and will attach itself to the drop. A positive ion, on the other hand, will be pushed aside and will have to go round the drop before it comes into the field of attraction of the negative charge on the upper surface of the drop. The mobility of positive ions is, however, low compared with the wind velocity, with the result that they will be unable to turn back to the drop but will be blown past. By this selective capture of negative ions the drops become negatively charged and form the lower negative or *N* charge centre. The air which is blown upwards will remain with an excess of positive ions, which go to form the upper positive or *P* charge centre. However, when more data became available about the life history of thunderstorm cells it was found that the Wilson process alone was too slow to produce the observed charge separation in the available time.

A thundercloud contains water vapour, large and small water drops, and large and small ice particles—some dry and some wet. The drops and ice particles have widely varying temperatures, and are in a state of turmoil, caused by the strong air currents in the cloud. Laboratory experiments have shown that electrical charges can be separated by various reactions between the different constituents of the cloud.

Friction between ice particles of different size generates electricity, but the reaction depends upon the difference in temperature between the colliding particles and also on their state of contamination by dissolved substances. It does not therefore lend itself to quantitative estimation.

When an ice particle grows by sublimation from water vapour it may give off small splinters of ice, the main particle acquiring a negative and the splinters a positive charge. The splashing produced when a large drop of water collides with a hailstone and becomes partly frozen to it gives a negative charge to the hailstone and a positive charge to the spray of droplets.

When small supercooled droplets impinge on an ice particle they get frozen on to the particle, which then acquires a negative charge, and the air becomes positively charged. Some support for considering such a riming process as at least partly responsible for the charge separation in thunderclouds is found in the observation, already noted, that the negative column of charge extends to the $-40°$ C level, above which height water cannot exist in liquid form, and riming is thus impossible. Any of these processes of charge generation causes negative charge to be collected on the larger and positive charge on the smaller particles, so that separation of the respective charges can be effected by gravity. The heavier and negatively charged particles will tend to fall downwards, whereas the lighter ones will be carried towards the top of the cloud by updraughts.

A number of other explanations for the electrification of thunderclouds have been advanced, but points of objection can be raised against all existing theories.

The origin of the small positive charge in the base of the cloud is less obscure, and it seems fairly certain that there are two contributing processes. Firstly, positive ions due to point discharge at the ground are carried upwards by rising air currents into the base of the cloud, where they become attached to, and immobilized by, the water drops. Secondly, large drops in the base of the cloud tend to be shattered by the updraughts, and by virtue of the waterfall effect the resulting debris of smaller drops acquires a positive charge.

In conclusion, a thundercloud may be likened to an enormous witch's cauldron of which we now know the ingredients and the final products. Much more information will have to be forthcoming, however, before the connection between the two is fully understood.

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Fourcroy and the anti-phlogistic theory

W. A. SMEATON

The overthrow of the phlogiston theory was of profound importance to the history of science. The chief credit must go to Lavoisier, but it is not always realized that his ideas were long opposed. That they ultimately became generally accepted is due in large measure to Fourcroy, through his dispassionate and brilliant assessment of the evidence. Marat sneered at Fourcroy as Lavoisier's 'little disciple, who propagates these fine theories in the four corners of Paris', not recognizing this as one of the most important scientific tasks of the day.

Antoine François de Fourcroy was born in Paris on 15th June 1755 and became a medical student there about 1773, when Lavoisier was beginning his great series of researches on combustion and calcination. From his earliest teachers of chemistry Fourcroy doubtless learned that all inflammable substances and metals contained phlogiston, a 'principle' that was emitted during combustion and calcination and was transferred from one substance to another in many reactions. Fifteen years later, he himself taught that nothing was emitted during combustion, but that combustible materials combined with oxygen, one of the constituents of the atmosphere. These are the fundamental statements of two great systems of chemistry. The difference between them is profound. Phlogiston was a principle that could never be obtained in isolation, and to which contradictory properties were assigned by different chemists. By contrast the anti-phlogistic theory was based on the study of a substance that could be isolated, weighed, and examined by ordinary chemical and physical means.

The experimental discoveries of many scientists contributed to this revolution in chemistry, but credit for the foundation of the anti-phlogistic theory belongs to Lavoisier, who gradually built it up in a long series of papers published from 1773 to 1787. Lavoisier's writings were read by those who consulted the scientific journals, but his work was widely known outside scientific circles, and after the new theory was perfected it spread rapidly throughout the world. It was Fourcroy who was mainly responsible for this wide dissemination of the anti-phlogistic theory.

Fourcroy's family was not rich; after leaving school he became a clerk, and might have remained in obscurity if he had not met F. Vicq d'Azyr (1748–94), who was beginning his career as a doctor and anatomist. Vicq d'Azyr was impressed by the young clerk and persuaded his father to allow him to study medicine. A brilliant student, Fourcroy received much encouragement and financial support from the members of the *Société Royale de Médecine*, of which Vicq d'Azyr was secretary. Most of the members were young doctors interested in the scientific aspects of medicine, and among them was J. B. M. Bucquet (1746–80), professor of chemistry in the Faculty of Medicine in Paris.

Following Vicq d'Azyr, Fourcroy was at first interested in anatomical research, but Bucquet's influence became stronger, and he soon decided to concentrate on chemical research and teaching [1]. He worked in Bucquet's laboratory, and began his career as a lecturer one day in 1778 by taking Bucquet's place when the latter was ill [2].

In the winter of 1778–79, before he had graduated, Fourcroy gave his first annual course of lectures, in which he adopted Bucquet's method of combining chemistry and natural history. He soon became known as an excellent lecturer, and his reputation was increased by the appearance in 1782 of his first book, *Leçons élémentaires d'histoire naturelle et de chimie*, which was translated into English and Italian. After Bucquet's death in 1780 Fourcroy would have been a worthy successor to his chair, but by his close association with the *Société Royale de Médecine* he had incurred the disfavour of the senior members of the Faculty, who were opposed to certain activities of the *Société*. On graduating in 1780 he was refused the title of *docteur régent*, without which he could not teach in the Faculty. This may ultimately have been to Fourcroy's advantage, for he had as a result to develop courses dealing with all branches of chemistry, while as professor in the Faculty he might have concentrated on the medical aspects of the subject.

In his last years Bucquet carried out much research in collaboration with Lavoisier, and was

probably the first chemist to adopt Lavoisier's theory, which he taught in his final courses of lectures [3]. Fourcroy took part in some of this joint research, and he too favoured Lavoisier's theory as early as December 1777, when, after reviewing the history of the theory that metallic calces contain air, he wrote: 'Finally, by many experiments which are as ingenious as they are exact, M. Lavoisier showed that calcination is nothing but the absorption by the metal of an elastic fluid contained in the air, and that the reduction of a metallic calx is only the release of this fluid. . . .' [4].

In a medical thesis presented on 15th June 1778 Fourcroy [5] also stated that the illustrious Lavoisier had proved that air is a mixture of two gases. By 1782, nevertheless, he was no longer convinced that Lavoisier was correct in rejecting phlogiston. In the preface to the *Leçons élémentaires* Fourcroy explained that one of his objects was to compare the phlogistic and the new theories, declaring that he neither rejected the one nor adopted the other. He stated that he considered Lavoisier's theory to be the more convincing at that moment, since it appeared to proceed solely from confirmed facts. The new theory was still far from perfect in 1782, and Fourcroy thought that many phenomena were better explained by P.-J. Macquer (1718–84). In 1777, in the second edition of his *Dictionnaire de chimie* [6], Macquer had expressed the opinion that during combustion and calcination the absorption of part of the air was accompanied by the emission of phlogiston, which he considered to be identical with light. This theory too had its defects; Fourcroy pointed out, for example, that some metals could be calcined without visibly emitting light.

FIGURE 1 – *A. F. de Fourcroy*, 1755–1809. *From a lithograph by Bonhomme, after a portrait by David.* (*By courtesy of the Bibliothèque Nationale, Paris.*)

The uncertainty about the origin of the light emitted during combustion was perhaps the chief reason why Fourcroy in 1782 could not wholeheartedly adopt the theories of either Lavoisier or Macquer. Five years earlier he had accepted the theory that air, or a part of the air, was absorbed, but since then Lavoisier had advanced the theory that the matter of fire or light (a weightless fluid, which he later called caloric) was present in all gases, and was released from oxygen during combustion. Fourcroy considered that the presence of fire or light in oxygen was no more proved than the presence of phlogiston in combustibles. It was not until the caloric theory had been put on a quantitative basis, and considerably modified, as a result of the researches on calorimetry by Lavoisier and Laplace, that Fourcroy was able to accept this part of the anti-phlogistic theory.

A note written in 1785 shows [7] that Lavoisier appreciated Fourcroy's book. In this the new theory, at a crucial stage in its development, was presented to a large number of readers and criticized with an impartiality that was rare in eighteenth-century textbooks, and indeed in the textbooks of any century.

The private courses given in Paris by Fourcroy and some of his contemporaries were attended by only small numbers of serious students, but audiences running into hundreds came to hear Macquer's public courses at the *Jardin du Roi* (now the *Muséum d'Histoire Naturelle*). After Macquer's death in 1784 there were two candidates for the chair—Fourcroy and Berthollet (1748–1822). Berthollet was the older man and a member of the *Académie des Sciences*, but Fourcroy, with his considerable reputation as a lecturer, was preferred. Berthollet, who was much interested in the industrial applications of chemistry, successfully filled

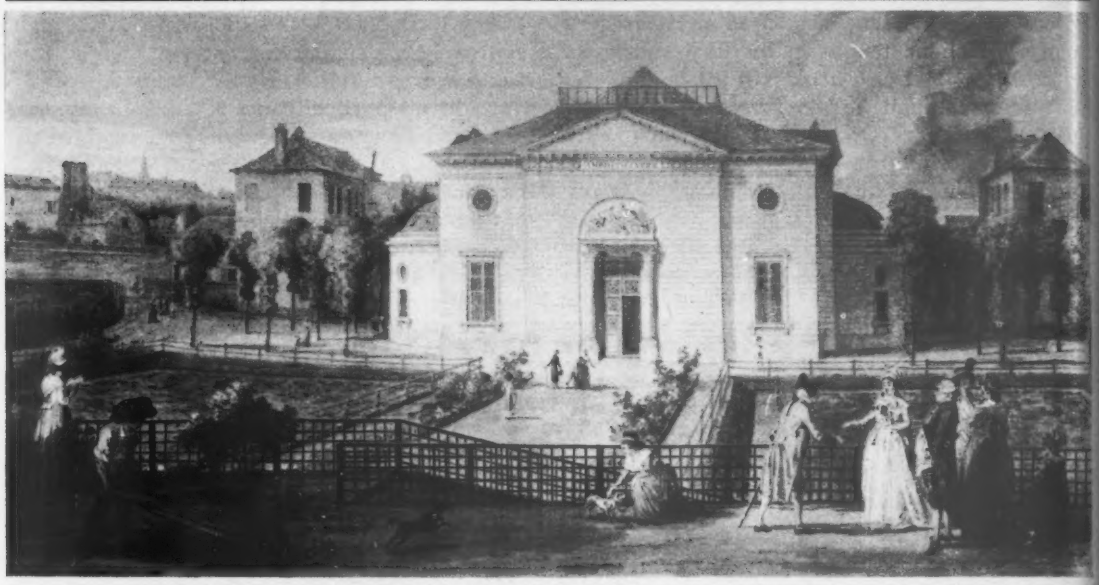

FIGURE 2 – *The amphitheatre of the Muséum d'Histoire Naturelle in* 1795, *from a painting by B. Hilair. (By courtesy of the Bibliothèque Nationale, Paris.)*

Macquer's other post as director of the Gobelins dyeworks.

Soon after his appointment Fourcroy pointed out to a friend that at the Gobelins works Berthollet occupied the best-paid scientific post in France, with an annual salary of 6000 livres, while he himself earned only 1500 livres at the *Jardin du Roi*. He contrasted these figures with the emoluments of high government officials, who sometimes received as much as 100 000 livres, and complained bitterly that scientists were not well enough paid [8]. Fourcroy's books and his private courses added considerably to his income, but it was not until after 1800, when he was a Councillor of State, that he became a fairly rich man.

A new amphitheatre, with room for 1200 people, was built at the *Jardin du Roi* in 1788, and it was in this building that Fourcroy achieved fame. For a quarter of a century very large audiences from all lands were inspired by the great teacher who was also a great orator. Fourcroy came to the *Jardin du Roi* at a time when chemistry was being rewritten; fortunate indeed were those who could follow its progress from his lips.

On 31st July 1784 Fourcroy asked the *Académie* to approve the manuscript of the second edition of his textbook, now called *Elémens d'histoire naturelle et de chimie*. In this he again compared the phlogistic and anti-phlogistic theories, without definitely adopting either. It was not until 9th July 1786 that the report on the work was presented to the *Académie* by Lavoisier and Sage, and when published shortly afterwards the book contained a long preliminary discourse, in which Fourcroy showed that he now completely accepted the anti-phlogistic theory. During the intervening two years the new theory had been greatly strengthened by the discovery of the composition of water and of nitric acid. Moreover, in May 1785 Fourcroy had been elected to the *Académie* and brought into regular contact with Lavoisier and with Berthollet, who was converted some time before Fourcroy.

In April 1786, probably just after his acceptance of the new theory, Fourcroy gave for the first time a short course on the chemistry of gases, which served as an introduction to his general chemistry course. His friend Bouvier wrote out the contents of the course, and the manuscript was revised each year, sometimes by Fourcroy himself, as the lectures were modified to include the latest discoveries concerning gases. Fourcroy intended to publish the course when the subject had reached a fairly steady state, but this was never done. The manuscript shows that the course was a very useful introduction to anti-phlogistic chemistry, and provides further evidence of Fourcroy's skill in presenting his subject in an original and interesting manner [9].

Early in 1787 Lavoisier and his converts were joined by L. B. Guyton de Morveau (1737–1816), who in 1782 had presented a partial reform of

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chemical nomenclature. Fourcroy collaborated with de Morveau, Lavoisier, and Berthollet in preparing a comprehensive system of nomenclature, in which the name of each substance expressed its composition according to the new theory [10]. Fourcroy's contribution was small, but he greatly helped to bring about the rapid adoption of the new nomenclature by using it in the many books that he subsequently wrote.

The first of these was *Principes de chimie*, published in 1787 as part of the *Bibliothèque universelle des dames*. This little book, though elementary, is of considerable interest, for it was the first to be written entirely according to the new theory. Phlogiston was not even mentioned, only the new nomenclature was used, and the contents were systematically arranged according to the composition of the substances discussed. A suitable introductory textbook for any student, it was reprinted in 1787. In 1788 Fourcroy had some copies reissued, with a different title-page and preface, for the students of the Veterinary College at Alfort, where he had been professor of chemistry from 1783 to 1787.

The subject-matter was better arranged in the *Principes de chimie* than in the *Elémens*, where substances were classified according to their mode of occurrence in nature. Fourcroy realized that the new method was superior, but did not use it in the new editions of the *Elémens* published in 1789 and 1791 and reprinted twice in 1793, probably because he or his publisher was unwilling to make a fundamental change in a book that was still selling well. There was a very great interest in the new chemistry in Paris, and Fourcroy taught it not only by means of his books and his lectures at his laboratory and the *Jardin du Roi*, but also in the *Lycée* of the rue de Valois, a private institution for higher education in which he occupied the chair of chemistry from 1787 until 1807 [11].

Fourcroy's activities were sarcastically described in a bitter criticism of members of the *Académie des Sciences* published in 1791 by J. P. Marat, the revolutionary leader. Marat had a long-standing grudge against the *Académie*, which had not given its approval to his scientific publications. An attack on Lavoisier and his work was followed by a description of Fourcroy as 'his little disciple, who propagates these fine discoveries in the four corners of Paris' [12]. But the revolutionary politicians rapidly changed their opinions, and it was after being nominated by Marat that Fourcroy was somewhat reluctantly elected in 1792 as a substitute deputy to the National Convention, the republican parliament. Ironically, when he entered the Convention in July 1793 it was to occupy the seat left vacant by the murder of Marat.

Fourcroy added to his burden of work by undertaking the great task of completing the chemical section of the *Encyclopédie méthodique*, which was intended to replace Diderot's *Encyclopédie*. The first of the six chemical volumes was written by de Morveau, but in 1790 he was appointed to an important administrative post and temporarily abandoned his scientific work. Fourcroy was able to publish the second volume in 1792, but many delays were caused by the Revolution. The sixth volume, completed by N.-L. Vauquelin (1763–1829) after Fourcroy's death, did not appear until 1815.

A systematic teacher, Fourcroy was always trying to find the first principles of chemistry and arrange them in a methodical way, and in the second volume of the *Encyclopédie méthodique* he included an article, '*Axiomes*', in which he classified the chief facts of chemistry under twelve headings. This article, of about 25 000 words, was reprinted in the same year as a small volume entitled *Philosophie chimique*. Under each heading Fourcroy gave a very clear, but necessarily brief, account of the substance or phenomenon named. Each account consisted of a series of propositions, with no suggestion that any of them might be controversial. This book was written in a very concise style, in marked contrast to some of Fourcroy's writings, which were often verbose, even by eighteenth-century standards.

For the details of chemistry it was necessary to consult a book of the conventional sort, but as a guide for the student, or for the older chemist who was uncertain of the anti-phlogistic theory, the *Philosophie chimique* was without a rival. It enjoyed a success that astonished its author. By 1799 about 8000 copies of the two official Paris editions had been sold, as well as pirated copies. However, in a letter to J. B. A. Scherer, Fourcroy said that he had made little financial profit because he had deliberately kept the price low at a time when paper was very expensive [13].

Between 1793 and 1797, when he was active in politics, Fourcroy did little research and wrote no new books, but he worked very hard in promoting the applications of science to the industry and war effort of the young republic, and in developing advanced scientific and technical education. He played a large part in the foundation in Paris of the *Ecole Polytechnique* and the *Ecole de Médecine*, and in each of these he occupied a chair of chemistry

which he retained, with that in the *Muséum d'Histoire Naturelle*, until his death. He was also largely responsible for the effort to introduce serious scientific courses into the secondary schools [14].

Fourcroy resumed all his scientific work in 1797, and until his death on 16th December 1809 he performed a great deal of useful research, mainly in collaboration with Vauquelin, his former student. His chief interests were the chemistry of animal substances and the applications of chemistry to medicine.

The third chemical volume of the *Encyclopédie méthodique* appeared in 1797, and in this Fourcroy included a great article, entitled simply '*Chimie*', in which he gave a long account of the history of the subject. The chemistry of the late seventeenth and eighteenth centuries required 387 closely printed quarto pages. This account remains to this day an extremely valuable source of information, particularly for the development of the anti-phlogistic theory, for which Lavoisier was given the full credit. However, it is noteworthy that although Fourcroy was the leading exponent of the anti-phlogistic theory, he considered Stahl, the founder of the phlogistic theory, to be the father of chemistry, for he had given the subject its first great unifying theory.

Fourcroy also wrote a completely new treatise, *Système des connaissances chimiques*, which was published in 1800 in editions of ten octavo and five quarto volumes respectively. This great work, not intended for beginners, contained a vast amount of information about the chemistry of all known substances, systematically arranged according to their composition; but it was regarded by Fourcroy only as the first part of a much larger work, and was intended to be followed by three further treatises concerning the history, the practice, and the applications of chemistry. This project was never completed, but in the *Connaissances chimiques* Fourcroy included many references to the history and applications of chemistry. A summary of the work was published by Fourcroy in the form of a series of tables, entitled *Tableaux synoptiques de chimie*, which, like the *Connaissances chimiques*, was translated into several languages.

In 1800 Fourcroy became a member of Bonaparte's Council of State. He was soon appointed Director-General of Public Instruction, and again spent much of his time organizing the educational system. He continued his lecturing and research, in collaboration with Vauquelin, but wrote no new books. However, he found time to publish an enlarged edition of the *Philosophie chimique*, which was printed three times in 1806. Various editions of this work were translated into eleven foreign languages, and students in all countries from Brazil to Russia obtained from it their introduction to the anti-phlogistic system of chemistry.

The many translations of Fourcroy's books show that his influence was greater than that of any other chemical writer of the day. English translations were particularly numerous. All the editions of the *Elémens*, the second and third editions of *Philosophie chimique*, the *Système des connaissances chimiques*, and the *Tableaux synoptiques* were published in London or Edinburgh, and they must have been the books most commonly used by English and Scottish students until the appearance of Thomas Thomson's 'System of Chemistry' in 1802. Another country where Fourcroy's influence was strong was Italy, where at least five translations of *Philosophie chimique* were published.

Fourcroy's books deserved their popularity. As a propagandist for the anti-phlogistic theory he had no rivals, and it is remarkable that he was able to combine his lecturing and writing with his research, which was by no means insignificant, and with a very active public life.

ACKNOWLEDGMENT

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Salt marshes

J. A. STEERS

Salt marshes—and mangrove swamps, which are their tropical equivalents—are areas of natural land reclamation. Geographical and ecological changes occur extensively and very rapidly in them. This article describes the changes in land structure and vegetation as they occur both on the coasts of Britain and America and in the mangrove swamps.

In the shallow waters of many marine inlets, and especially behind sand and shingle bars, conditions are often favourable to the deposition and accumulation of thick deposits of mud and salt. Algae and higher plants begin to colonize the mud flats and a carpet of vegetation spreads over large areas. The plants themselves collect silt, and so there is an interaction of physical and ecological factors at all stages in the development of a marsh. The nature of the plant cover depends in part upon the kind of deposit that is laid down, which may be sand or mud. Plant growth is also closely connected with tidal conditions. At high water of spring tides the whole marsh is covered, but it is exposed at low water. During neap tides, when the range of movement is less, the higher parts of a marsh are not covered, but the low parts may remain submerged for several days. The incidence of flooding tides at certain times of the year is an important factor in the distribution of seeds. In tropical areas the mangrove swamp is the counterpart of the salt marsh of temperate latitudes, and again its spread leads to the formation of new land.

The marshes on the east coast of Britain are usually characterized by thick and fairly compact mud based on sand flats. On the coast of Wales there is far less mud, and the marshes are predominantly sandy. On the south coast many marshes are built up of soft mud and may be treacherous.

Two of our best-studied marshlands are those on the Norfolk coast and those in the Dovey (Dyfi) estuary. Along the Norfolk coast between Hunstanton and Weybourne the water is shallow, and bars of sand and shingle have formed offshore. Scolt Head Island and Blakeney Point are the two best known. Behind the bars there are areas of quiet water in which sediment, carried by the tides, is deposited. The spits and bars are complex structures, having on their landward sides several lateral ridges or hooks. Thus the protected area within is further subdivided.

Scolt Head Island (figures 1–13) shows the stages of marsh growth very well. The island consists of a main shingle ridge with laterals, all built on sand flats. Sand dunes have later formed on these ridges. The island has grown from east to west, although storms may occasionally cut off parts of its western end. At this end there are the newest shingle ridges, enclosing bare sand flats just beginning to show the first stages of marsh formation. The tide ebbs and flows over them and carries a large amount of fine material in suspension. Some of this is dropped near the limits to which the water reaches, some around patches or rolls of seaweed; lugworm (*Arenicola*) casts may cause local deposition, and some material falls on the slightly higher parts of the sand flats. For a few years there may be little noticeable change, but in course of time the patches of mud, as the result of their outward and upward growth, begin to form ill-defined islands. Seeds reach them, carried by water, by birds, and often by man, and under appropriate conditions plant growth begins. On a substratum of sandy mud *Salicornia* (samphire) and *Suaeda maritima* (herbaceous seablite) or locally *Puccinellia maritima* (sea poa) are most likely to be the pioneers. On soft and wet mud *Zostera* species are usually the first arrivals. The plants themselves soon become obstructions and induce further deposition, and, gradually, the tide is more and more enclosed between ill-defined mud banks partly covered with plants. As the banks grow higher and unite, the water is increasingly confined to the embryo creeks.

The drainage pattern of a marsh is best seen from the air (figure 13). The creeks, unlike rivers, have not cut their valleys; they are unenclosed parts of the surface on which marsh has grown. Their pattern is complex, but is like that of a river system, since there are major creeks into which a large number of winding tributaries drain. The bottoms of the creeks, especially of the larger ones, are part of the substratum. As the marsh grows upwards, fewer tides cover all of it, and this affects the spread of vegetation. A walk from the lower

to the upper levels of a typical Norfolk marsh shows this. The bare mud flats with algae give place to a vigorous growth of *Salicornia* and *Suaeda maritima*; *Aster tripolium* (sea aster) follows this association or indeed may accompany it. On the mud surface, and entwined among these plants, there is often a mat formed of two rootless seaweeds—*Pelvetia canaliculata* and *Bostrychia scorpioides*. There is thus a dense carpet of vegetation, and it is at this stage, when inundations occur at every high water, that accretion goes on most rapidly. If the surface consists of soft mud, *Zostera* species may take the place of *Aster* and *Salicornia*. If the surface is markedly sandy there may be a vigorous growth of *Puccinellia*. At higher levels the sea pink (*Armeria maritima*), the sea arrow grass (*Triglochin maritima*), the sea spurrey (*Spergularia maritima*), and species of sea lavender become prolific. At the highest levels the plantains (*Plantago maritima* or *P. coronopus*), the wormwood (*Artemisia maritima*), and certain species of rush are the commonest plants.

Along the creeks, once they have become fairly well defined, *Halimione portulacoides* (sea purslane) is especially characteristic. This is a low-growing bushy plant with sage-coloured leaves that begins to spread from the creek edges, where drainage is good. It is strong and vigorous and often spreads over large areas of marsh and smothers all other vegetation.

A walk from west to east across the marshes at Scolt Head enables one to compare their heights and relative ages. Those first encountered are almost bare sand flats; then follow those on which only a thin layer of mud has gathered and in which the creek system is embryonic. Next came those in which the mud layer is an inch to a foot or more thick. Where the mud is fairly thick, such marshes are almost completely covered with vegetation and intersected by numerous creeks. Although the creeks originate by the upward and outward growth of marsh, there are places where they lengthen backwards as a result of erosion at the head. If a marsh grows on a gently sloping sand-flat, it may cover the lowest part some time before the upper part. Flooding tides, however, cover the whole, and at the ebb the water is concentrated into the heads of channels and cuts them backwards.

Salt pans are features of nearly all marshes. They are small lakes and of two main types. Some are elongated, and clearly have originated by the interruption of a creek by small dams produced by the growth of vegetation or perhaps by a collapse of the creek bank. The other type is usually round or oval, but sometimes irregular. They are residual hollows; the vegetation spreads over the surface of the marsh in such a way as to enclose parts of it that are without vegetation. As the marsh increases in height the hollows become better defined, and because they are not drained they remain bare. If a small channel is cut to them, so that the water can drain out instead of remaining as a pool after spring tides, they become covered by plants in a year or two and reveal themselves as a very slight depression in the marsh surface.[1]

The marshes in the Dovey are typical of many on the west coast, and their setting in an estuary in a mountain area is a striking contrast to those on the flat coast of Norfolk. The zoning of plants is as noticeable as in Norfolk, but the rarity or even absence of some of the plants on the East Anglian marshes gives them a very different appearance.

The thin layer of mud on the sand, the greater amount of grass marsh, and the scarcity of colour are noteworthy. Since the grass is locally grazed during neap tides, when the sea does not flood the marshes, the surface is often lawn-like. The thin upper layer of finer sediment is held together by roots, and, since it is easily undercut and falls into the creeks, these are unlike those in East Anglia. On the south coast the softness of the mud and the abundance of *Spartina* give the marshes a unique appearance. Readers familiar with Southampton Water and Poole Harbour will realize how rapidly *Spartina* has spread and converted extensive areas of bare, soft mud into green marsh. There are native species of *Spartina*, but *S. townsendii* is a hybrid between the native *S. maritima* and the American *S. alterniflora* and was first noted in Britain in 1869.

Because *S. townsendii* is a remarkably good accretor of mud and silt it is often planted in suitable places to encourage the growth of marsh, either for reclamation purposes or as a factor in sea defence. Unfortunately it has now reached several parts of the Norfolk marshes, where, because of its hybrid vigour, it will, unless checked, spread and bring about great and unwelcome ecological changes.

The vertical thickness of marsh deposits depends primarily on two factors. On a stable coast the thickness is governed by the tidal range. The higher a marsh grows the less it is covered by the tide; its upper limit is governed by the highest tides that cover it. The depth will vary with the slight undulations of the surface on which it has

[1]Some pans have a soft floor of spongy mud. Adequate reasons for this are not known, but the softness may be connected with certain organisms.

grown. If, however, a coast is sinking, marsh deposits may reach a much greater thickness. The nature of the marsh surface depends a good deal on the rate of sinking. If the upward growth of the marsh equals or exceeds the downward movement of the land or the rise of sea level, the surface appearance will be that with which we are familiar in many of our marshes. If the sinking becomes greater than the growth, the marsh will be swamped and may only appear as a narrow fringe adjacent to the land. If an upward movement of the sea floor occurs, or if there is a fall in sea level, the marsh will soon become dry land.

Since the species of plants growing on a marsh depend in part upon the number of tidal inundations, it follows that if, in a vertical section or bore made in a marsh, traces of plants characteristic of lower zones are found above those belonging to higher ones, a downward movement of the land or rise of sea level may be inferred. Marshes may afford useful means of estimating vertical movements of a coast in unsurveyed lands.

The rate at which marshes grow upwards has been measured in several places. A thin layer of some distinctive material, for example a coloured sand, is spread in patches about a metre square on the marsh and vegetation. If this is done just before a big tide the water will wash the sand off the vegetation, and it is then easy to smooth the patch so that it lies on the marsh surface like the jam on the lower half of a sandwich. All the patches should be marked by a stake driven into the marsh about a metre from them, and they should be carefully levelled. After a period of years they are investigated, either by cutting with a knife, or by pushing a sharp hollow tube into the marsh in such a way as to bring up a small core. The amount of sediment accumulated on the sand can be readily measured. It will vary from place to place. It is usually greatest on low to medium–high marshes densely covered with plants and inundated by most high waters. At higher levels the number of inundations falls off, and the increase in the height of the marsh is slower. At low levels it is usually impossible to use this method, since the sand is washed off bare mud. Table 1 gives some idea of the rates of growth in two different areas.

Many marshes are partly surrounded by dunes. Where this is so, sand may be blown over the marsh, and some may be washed over low dunes in big tides. This helps their upward growth. Occasionally a shingle ridge is breached, and pebbles and other coarse material spread over the marsh surface. Both events illustrate how mixed types of sediment can be produced.

Perhaps the most extensive development of salt marshes in the world is that along the eastern

TABLE I

SCOLT HEAD ISLAND (J. A. Steers)

Missel Marsh is covered by most high tides and the vegetation is mainly *Salicornia*, *S. maritima*, and *Aster tripolium*. *Halimione portulacoides* is beginning to spread from certain creeks. The measurements of sedimentation thickness began in 1935 (September), and the following figures apply to stations at which records were taken in three different years. No. 1 station is at the top of the marsh.

Station No.	1937 (cm)	1947 (cm)	1957 (cm)
2	1·25	8·5	20·0
3	1·25	7·5	17·0
4	1·75	12·5	22·0
9	1·70	9·4	14·0
10	2·50	14·0	23·0
14	1·72	10·0	20·0
16	1·55	11·3	15·0
20	1·72	11·0	19·0
21	1·80	10·5	23·0
22	1·63	10·5	20·0
23	1·60	11·5	17·0
26	1·85	9·8	18·0
30	1·95	12·0	19·0
32	1·60	10·5	17·0
34	1·60	12·5	20·0
35	0·75	10·5	22·0

DOVEY MARSHES (F. J. Richards, *Ann. Bot.*, 48, 225, 1934)

The measurements covered 100 and 54 months respectively, and the two lines crossed all the zones of vegetation.

Line 1, *ca.* 400 ft long.

Association	Accretion (cm in 100 lunar months)	No. of observations
Glycerietum	6·61	8
Transition *Glycerietum-Armerietum*	5·53	7
Armerietum	3·53	30
Transition *Armerietum-Festucetum*	2·00	1
Festucetum	1·75	4
Juncetum	2·03	3

Line 2, *ca.* 250 ft long.

Association	Accretion (cm in 54 lunar months)	No. of observations
Glycerietum	3·67	6
Glycerietum-Armerietum	6·93	2
Armerietum	4·09	15
Festucetum	3·38	6
Festucetum-Juncetum	4·60	1
Juncetum	2·25	1

NOTE. The suffix *-etum* is added to the root of the word to denote the dominant plant in the association.

FIGURE 1 – *Sand flats: beginning of a thin layer of mud. Algae in rolls. A very early stage in marsh formation. (Figures 1–13 refer to Scolt Head Island, Norfolk.)*

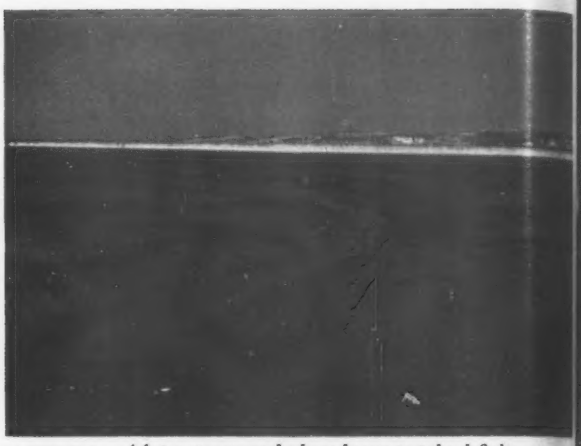

FIGURE 2 – *A later stage: creeks have begun to take definite courses, but vegetation is still mainly algal.*

FIGURE 3 – *Vegetation zones on lower Missel Marsh. Sea aster invading* Salicornia *and* S. maritima. *Algae and bare mud at lowest levels.*

FIGURE 4 – Salicornia *marsh: a marsh in a young stage of development. It is enclosed by shingle ridges and the vegetation (1958) is rapidly changing,* Salicornia *giving place to sea lavender,* Spartina, *etc.*

FIGURE 5 – Suaeda fruticosa *commonly grows at the head of a marsh and the foot of a shingle ridge.*

FIGURE 6 – *Salt pans on Missel Marsh. The rounded form and definite outline are typical.*

FIGURE 7 – *A creek in Missel Marsh. The banks are lined with* Halimione, *and the mud banks in the creek, which are more frequently covered by the tide, are overgrown with* Salicornia, *etc.*

FIGURE 8 – Spartina *species, including* S. townsendii, *in Norton Creek.* S. townsendii *is spreading all too rapidly in the Norfolk marshes and completely changing their character.*

FIGURE 9 – *A creek in Missel Marsh which is lengthening 'backwards' as a result of being cut back by water draining into it as the tide falls and uncovers the marsh or flat above it.*

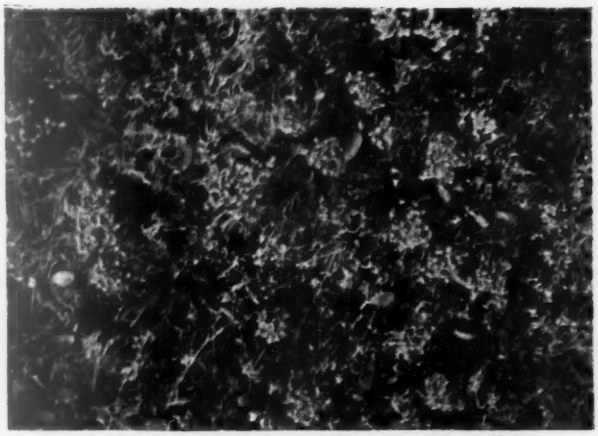

FIGURE 10 – *Sea lavender* (Limonium humile).

FIGURE 11 – *Spiral Marsh: a marsh with a narrow mouth between shingle ridges. The winding of the creek gives it its name.*

FIGURE 12 – *A general view over the Scolt marshes. The view is taken from a point on the highest dunes alongside the sea, looking towards Beach Point and Brancaster Staithe.*

FIGURE 13 – *Air photograph of a part of Scolt Head Island. The details of the marshes, creeks, pans, vegetation, and the shingle ridges are clearly visible.* (*Crown copyright reserved. Photograph: J. K. St. Joseph.*)

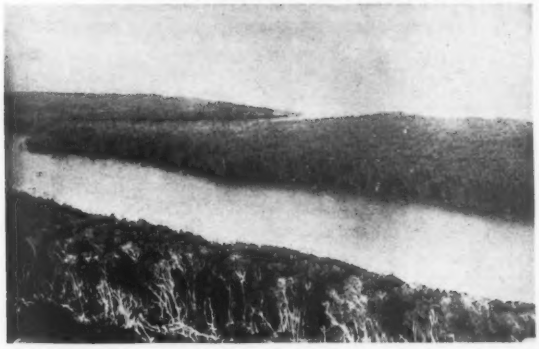

FIGURE 14 – *Detail of mangroves on the north side of Howick Island, Great Barrier Reef.*

FIGURE 15 – *Interior of the mangrove swamp, Newton Island, Great Barrier Reef.*

FIGURE 16 (*left*) – *Mangroves at the north-western corner of King Island, Great Barrier Reef.*

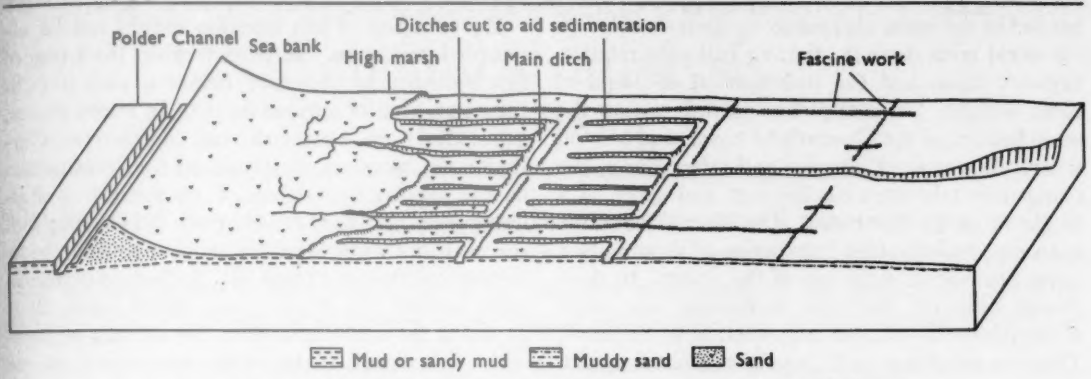

FIGURE 17 – *Schematic arrangement of sedimentary processes.* (*After F. Verger*)

coast of the United States. From Maine to Florida there is a magnificent development of offshore bars and beaches on which many seaside towns have been built. Within is a wide marsh area, intersected by many creeks and deep and ramifying inlets. A flight in an aeroplane along this coast is most revealing. The marshes vary from north to south, and three different types have been noted. In New England they consist mainly of bedded grey and brown salt peat with variable amounts of silt, which rests on deep brown or black brackish or freshwater peat. On the surface there are four main vegetation zones—*Juncus* at the top, followed by *Spartina patens*, the broadest zone, then *S. alterniflora*, and finally *Zostera* in a zone almost constantly submerged. Farther north, the Fundy marshes (named after Fundy Bay) are different and built up of a soft red mud or sometimes a hard silt. The surface is often bare, and even when there is vegetation it is rather sparse. A great deal of land has been reclaimed. The plants are similar to those in New England except that the *Zostera* zone is missing, possibly because of the strong tides, the range of which exceeds fifty feet in places. The mud is fairly firm, and derived from the soft sandstones and shales surrounding the bay. In the Great Tantramar marsh, eighty feet of mud overlie two feet of freshwater peat—a clear indication of subsidence.

South of New England, and extending into Florida, is the third type—the coastal plain marshes. They are characterized by *S. alterniflora*. The average thickness of the deposits is ten to twenty feet, and consist of a bluish-grey silt or clay, with little peat. It has been suggested that the softer rocks adjacent to the coast south of New Jersey afforded abundant silt for the formation of the coastal plain type, whereas north of New Jersey the rocks are more resistant, and the stream

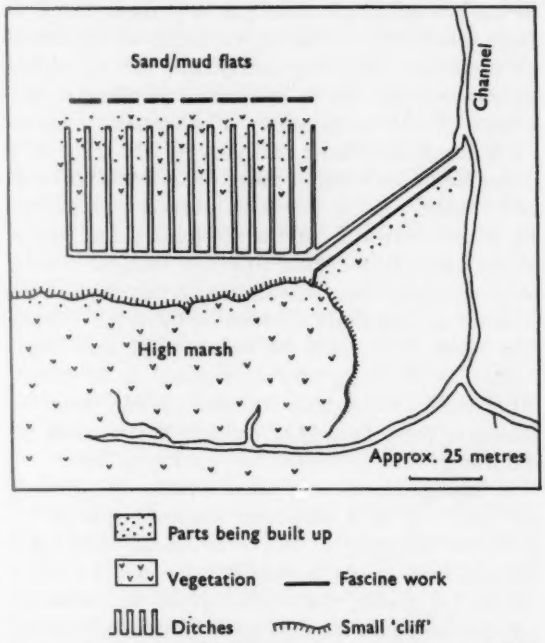

FIGURE 18 – *Simplified sedimentation scheme at Rejsby, Denmark.* (*After F. Verger*)

loads are dropped in lake and swamp. Thus the mineral sediment in the marshes is subordinate to the remains of vegetation, especially grasses.

In the tropics the mangrove takes the place of the low-growing plants of temperate latitudes. Hundreds of miles of coastline, especially in river mouths, are lined by mangroves (figures 14–16). They are typical of muddy coasts where there is some shelter and where the land is growing seawards. They are also found on coral and other reefs at some distance from land. Wherever they thrive they lead to the upward and outward growth of land, partly by trapping sediment

carried in the water and partly by their own decay. On coral reefs there is often an intimate relation between them and the stabilization of ridges of coral shingle. On many coral islands within the main barrier of the Queensland coast, and also on several cays around Jamaica and other places, the mangroves take root on the reef and grow to a height of 30–40 ft or more. The islands are in the open sea, and the first impression of them is of a forest growing directly out of the water. In their spread over the reef the mangroves are often accompanied by marine angiosperms, for example *Thalassia testudinum* and *Cymodocea manatorum*, and sometimes the grass *Spartina alterniflora*.

The word 'mangrove' is used in a double sense, for an ecological group of plants living in tropical tidal areas, and also for communities composed of these species. The trees and shrubs, like the plants of salt marshes, grow in zones according to the degree of tidal inundation. The pioneer is *Rhizophora mangle* (common mangrove), which forms a dense forest 30 ft tall or more. *Avicennia* follows at rather higher levels, but on coral reefs it may often be found seawards of the *Rhizophora* because it grows on slightly higher ridges of shingle. Along tropical coasts the *Avicennia* association grows best on land not regularly covered by the tide. Within this again there may be another species—*Conocarpus*. It is frequently accompanied by many other trees and grasses, but since it can often be shown to have developed on land first formed by the mangroves, it should be mentioned here.

A mangrove swamp shows how the growth and decay of trees and other vegetation, together with the trapping of silt, mud, sand, and even shingle, lead to the formation of new land. But the dismal glades, the equivalent of the creeks in salt marshes, and the dull green of the vegetation, to say nothing of the swarms of mosquitoes and other insects that often live in the mangroves, make them far less attractive than a British salt marsh. Yet, in both, new land is in process of formation, and if one wishes to reclaim the swamps and marshes it is a comparatively easy matter.

Reclamation of salt marshes should not be attempted too soon. A considerable thickness of fine sediment is necessary before a wall is built round an area of natural marsh. In many places, particularly in Denmark and north-west Germany, the marshes are prepared for reclamation by the digging or mechanical excavation of shallow dykes, and the throwing up of low ridges of the material excavated, so as to encourage sedimentation (figures 17 and 18). In Britain reclamations around the Wash have added more than 45 000 acres to our area since the Roman occupation. A journey to the Wash shows that as one approaches the coast the level of the land gradually rises. The same feature is seen all round the coasts of Britain where a wall divides reclaimed and open marsh. The former has settled and drained, whereas the latter is still accreting. If reclamation is carried out too quickly, the depth of fertile silt is insufficient. Sometimes reclamation is valueless. Large areas of Morecambe Bay were enclosed, but since they consisted of almost pure sand they were useless and were abandoned.

Salt marshes are of great interest to the physiographer because there are few places where changes go on so quickly and where they can be measured so effectively. Additionally their intimate relation with shingle ridges and sand dunes greatly increases their value as fields of study. To the ecologist they are significant because of the interrelation of the plant cover to substratum and tidal flooding. To the geologist they often present interesting illustrations of the ways in which very coarse and fine sediments can originate. To the coastal engineer the growth of a marsh suggests a protection for a stretch of coast, and the rapid growth of *Spartina* is a potent factor in reclamation. The study of marshes throws much light on vertical movements of the coast. They are also often places of great beauty. The ever-changing tidal conditions, the setting whether in a mountain-girt estuary or on an open coast, and the colours of the flowering plants—sea pink, sea lavenders, and sea aster—at different times of the year are unforgettable.

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X-ray fluorescence spectroscopy in chemical analysis

E. T. HALL

The theory of X-ray spectroscopy has long been understood, but the main progress in its application has taken place since 1945, stimulated by new apparatus and electronic circuits then becoming available. This apparatus, together with some of the results obtained by its use—which include the discovery of the nature of the Piltdown skull—are discussed here.

H. G-J. Moseley, in 1914, established the basic principles of X-ray spectroscopy, and later workers discussed its application to chemical analysis [1–4]. Five of the elements then missing in the Periodic Table (hafnium, technetium, rhenium, promethium, and francium) were discovered by this technique, but most of the progress in the field has been made since 1945 [5, 6]. This started with the development of new apparatus, such as low-energy Geiger counters and small high-power X-ray tubes, and has progressed to the commercial manufacture of X-ray fluorescence spectrometers.

BASIC THEORY

Early experiments relied on primary excitation of the specimen under investigation. In this technique the sample is made the target, or is smeared on the massive pure-metal target, of the X-ray tube. Electrons from the hot filament strike this target, causing it to emit X-rays which have an energy distribution similar to that shown in figure 1. The sharp peaks shown there are characteristic of the elements in the target, and these are superimposed on a 'white' continuum. The position of these peaks in the spectrum is the basis of qualitative X-ray analysis, while the height above the continuum will, in principle, indicate the amount of the target element present. The mechanism by which these excitation lines appear can be explained on the simple Bohr-Kossel model of the atom, in which the electrons surrounding the nucleus are distributed in shells designated as K, L, M, etc. Removal of an innermost (K) electron requires the most energy, and only when the bombarding electrons exceed a certain 'critical excitation voltage' will one of these electrons be ejected. Its place is immediately filled by an electron from an outer shell, and a K-series X-ray is released. L-series X-rays will be evolved at lower excitation levels when M-shell electrons replace those ejected from the L shell. Even though this is a much simplified picture, it is important to note that the number of possible lines for any one element are very much less than in the optical region of the spectrum. In practical spectrometry we are concerned with not more than five lines for any one element—the others can be neglected because of experimental limitations. The small number of measurable lines is a great advantage in most instances, since interference becomes less likely.

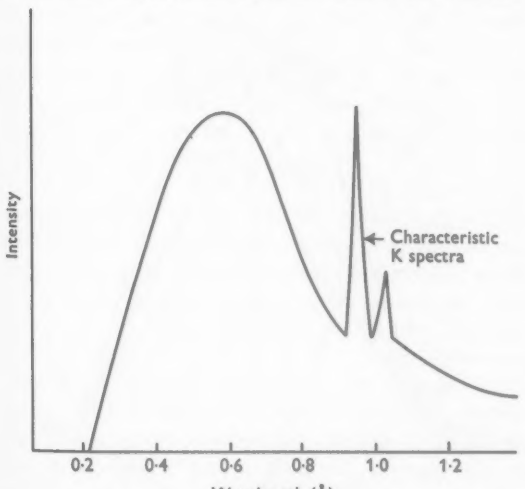

FIGURE 1 – *Continuous X-ray spectrum with characteristic lines superimposed.*

There are serious disadvantages in such 'primary X-ray' spectrometry, where the sample is inside the X-ray tube, on account of the difficulties associated with tubes that can be opened, thermal decomposition, and selective volatilization of the sample. In order to avoid these drawbacks we can resort to the phenomenon of 'secondary X-rays' or X-ray fluorescence. In this method the sample is outside the X-ray tube and it is

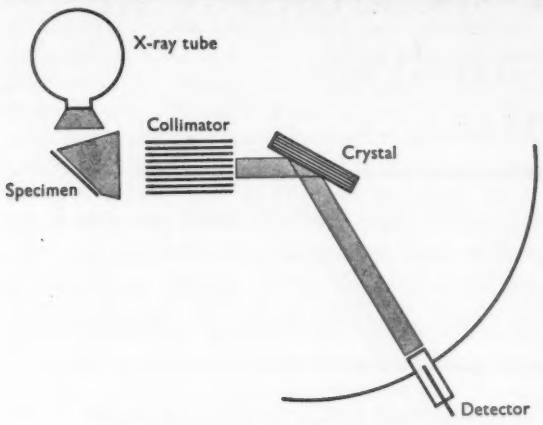

FIGURE 2 – *Flat-crystal spectrometer.*

irradiated with the primary 'white' radiation, which causes it to fluoresce with X-rays whose wavelengths are the same as those superimposed on the continuum discussed above; no continuum is excited in this way. A high proportion of the incident 'white' radiation is scattered, and the resultant characteristic peaks are very much reduced compared with those generated by electron bombardment. Nevertheless, ample intensity for accurate and quick quantitative analysis in many applications can be obtained by using the new high-intensity tubes and bombarding a large area of specimen.

Two main types of spectrometer are in use for resolving fluorescent radiation into its component wavelengths. Figure 2 shows the 'flat crystal' type. Here the secondary rays are collimated by long bundles of narrow thin-walled tubing or by parallel blades of thin sheet. The collimated beam strikes a large crystal of known grating constant, and when this crystal obeys the Bragg condition of reflection for a certain wavelength, a proportion of the rays with this wavelength will be reflected into the detector.

Under all other conditions, radiation of this wavelength will be scattered. The detector is geared to the crystal so that it is always in a position to receive the reflected rays. By slowly rotating the crystal and detector we can investigate the entire spectrum of the specimen.

This is an extremely simple type of spectrometer but suffers from attenuation of the beam incident on the crystal because of the collimation imposed by the slit system. Of course, the greater the resolution required the greater the collimation must be.

To increase this 'useful' intensity we can use a bent crystal, analogous to the concave reflection grating of the optical spectrometer. Figure 3 illustrates the principle. A point source of fluorescent rays irradiates an area of crystal that has been bent with its crystal planes on the circumference of a circle of radius R and has been ground with an inner surface of radius $R/2$. This inner surface is on a circle which passes through the point source. Radiation of wavelength λ striking the crystal planes at an angle θ will be focused again on the same circle as the source. Although this type of spectrometer gives a much enhanced reflection into the detector, the geometry of the system requires a more complicated mechanism than does the simple plane spectrometer. Moreover, since a point source is 'looked at' rather than an area of perhaps three square centimetres, a valuable integration factor is removed. Optical spectrographers will appreciate this difficulty, since sampling errors are a continual worry where only a small area is involved in the spark.

SCOPE AND LIMITATIONS OF THE METHOD

The energy of characteristic secondary X-rays varies with the atomic number of the element. If this energy is too small, the radiation will be unable to penetrate the air between the specimen and detector. This is so with elements of lower atomic weight than titanium. However, a vacuum or helium-filled spectrometer can be used for the elements between magnesium and titanium. For elements below magnesium even this technique will be unsuccessful, as the detector window will be too absorbent.

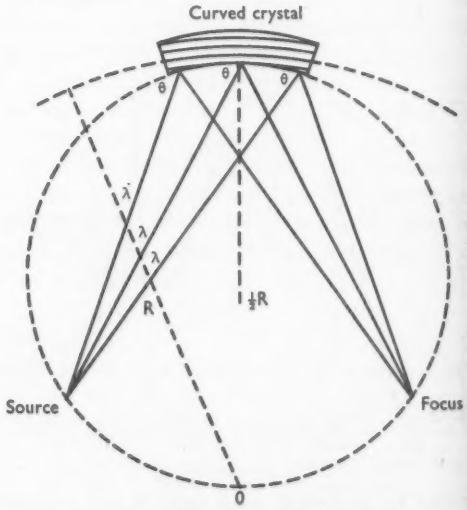

FIGURE 3 – *Curved-crystal spectrometer.*

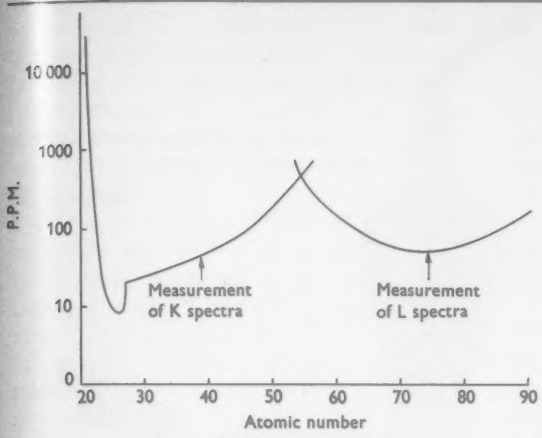

FIGURE 4 – *Curve showing sensitivity against atomic number.*

The sensitivity of the method for any particular element will depend on many factors, such as spectral resolution desired, reflectivity of crystal, type of detector used, and the energy of the primary X-ray beam. Moreover the main element of the target, when we are looking for a trace impurity, will have a large effect on the sensitivity. These variables make it difficult to compare the sensitivity of the method with that of other techniques. However, to give some idea, figure 4 shows the sensitivity of one particular instrument measuring all possible elements in an iron matrix, using an air-path spectrometer.

COMPARISON WITH OPTICAL SPECTROSCOPY

In order to assess the potentialities of this technique it is convenient to make comparisons with the optical spectrograph. In the writer's view the two techniques should be thought of as complementary—the time certainly has not arrived where the analytical chemist and optical spectrographer will be superseded.

The X-ray method is particularly valuable for elements above atomic number 20 present in concentrations ranging from 0·1 per cent to 100 per cent. The optical spectrometer, on the other hand, deals best with trace amounts from 0·0005 per cent to 5 per cent of most elements in the Periodic Table. The extension of the X-ray method to the elements of atomic number 11–20 presents difficulties which, although not insuperable, nevertheless render it inconvenient. However, emphasis should be given to the fact that concentrations above 10 per cent cannot generally be tackled by optical methods, whereas it is just such concentrations that are most favoured by X-ray spectrometry.

There is no doubt that as a non-routine laboratory tool X-ray methods are faster than optical ones, mainly because the photographic step is eliminated. They both require standardization techniques to obtain reliable results. However, direct-reading optical spectrometers, which use photomultiplier methods for obtaining quantitative results, are inherently as rapid as similar instruments that are just beginning to appear in the X-ray field. The non-destructive nature of X-rays as compared with the optical spark or arc may be important if one wants to examine either valuable specimens or finished manufactured goods.

The spectral line structure is infinitely simpler in the X-ray region. In fact there are some problems which can be solved only by the X-ray method because of line interference in the optical region; tantalum, niobium, and rare earth mixtures are notable examples.

In quantitative work the accuracy attainable by X-ray methods should be greater than that of optical emission methods. In X-ray spectrometry we are counting quanta arriving in a random fashion, and in order to increase accuracy all we have to do is to increase the total number of quanta recorded, that is, increase the time of counting. This means in practice that in order to get a 1 per cent accuracy of content, as little as one second devoted to a major constituent may suffice, whereas a minute per element may be required when estimating minor constituents. These times are remarkable when compared with the hours required for many conventional chemical analyses.

In both methods the state of chemical combination is immaterial, although standardization is best carried out under identical conditions. However, the author has found that good approximate results can be obtained using solutions in place of solids when this is possible, and standard solutions are relatively easy to prepare. In optical spectrometry, molecules not atoms are involved in excitation. The reverse is the case in the X-ray region. For this reason chemical combination is all-important in the former case, and results obtained with mixtures of salts or solutions may bear no relation to those obtained with the pure elements.

Optical equipment is now produced on a fairly large scale by several firms at a reasonable price. X-ray fluorescence equipment, on the other hand, is mainly supplied as an attachment to X-ray diffraction apparatus, which is not so satisfactory

as an instrument specifically designed for the job. Moreover, diffraction equipment involves a scanning technique, whereas in fluorescence we require measurements only on the top of known peaks. However, as has been stated above, direct-reading machines are just beginning to appear, and the prices of these are comparable with those of direct-reading optical equipment.

FIGURE 5 – *Modern automatic X-ray fluorescence spectrometer.*

FUTURE DEVELOPMENT

There are some interesting possibilities for the development of X-ray fluorescence analysis. Perhaps the most obvious improvement would be an extension of the method to elements of lower atomic number. This extension by the use of a vacuum spectrometer is an engineering problem which is now being solved. With suitable crystals and detectors, elements between aluminium and titanium will be estimated with the same ease as elements of greater atomic weight. The development of electron multipliers for elements lighter than aluminium is proceeding apace, and we can look forward in the next few years to having the whole Periodic Table covered by X-ray analysis.

Several workers are experimenting with non-dispersive X-ray spectrometry. Here, the use of pulse-height discrimination in the detector circuit may achieve the same result as spectral resolution by means of diffraction by a crystal. This would have two advantages—it would dispense with mechanical moving parts and also improve the counting speeds attainable, and hence the speed of analysis. There are, however, considerable practical difficulties.

The use of radioisotopes, instead of an X-ray tube and generator, as the exciting source of secondary X-rays from the specimen is an attractive possibility. Although the secondary yield will be considerably below that produced by a high-power X-ray source, the combination of stability, the avoidance of a bulky high-voltage generator, and the monochromatic nature of the exciting beam could offset this disadvantage in many applications.

Perhaps the most important development of X-ray spectroscopy during the last few years is that using the various electron microprobe techniques originating in work by R. Castaing [7–9]. In this method a beam of electrons as little as 1 micron in diameter is focused on the specimen, and the resulting characteristic X-rays are detected by a bent-crystal spectrometer. In this way the microstructure of metals and other materials can be studied in detail.

SOME APPLICATIONS

X-ray fluorescence analysis is particularly suited to archaeological specimens and other material where it is important that no damage is done to the specimen. Routine analyses of this kind have been proceeding for some years in Oxford at the Research Laboratory for Archaeology and the History of Art. One of the first problems presented was the analysis of the Piltdown skull fragments and flints. The question was whether the bones and flints had been artificially stained by an inorganic pigment in an attempt to imitate the ferruginous colour imparted to buried objects in the locality in which they were reported to have been found. It so happened that this was a perfect problem for the X-ray spectrometer, which in addition fulfilled the essential requirement of being non-destructive. The stain (if there was one) would be located on the surface of the specimen and thus, although present only in milligram quantities, would give a large amount of fluorescence compared with that produced by a similar quantity spread throughout the whole specimen. In fact, the skull fragments did give a significant chromium peak, as also did the flints, showing that the chemical was mainly on the surface. No comparable genuine fossils gave a

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similar peak. The conclusion finally reached was that the forger simulated true buried objects by boiling modern ape bones in potassium dichromate solution. The author has tried this and has obtained very similar results—both as to appearance and as to the readings obtained by X-ray fluorescence.

The fact that the surface of a specimen will contribute much more to the analysis than underlying layers can be an advantage or a disadvantage, according to the circumstances. In the tinplate industry, X-ray fluorescence of the iron can be used to measure the thickness of the tin layer above it. The primary X-rays striking the sheet of metal will be attenuated, as also will the secondary radiation from the iron on its way to the detector.

Conversely, in the archaeological field, when such objects as coins that have been buried for centuries are analysed one may find that the apparent analysis differs considerably from the average value found by such methods as γ-ray spectrometry. This is due to surface enrichment of one constituent at the expense of another. Values obtained by X-ray fluorescence must therefore be treated with reserve. Research now in progress at Oxford will try to elucidate this problem of surface enrichment. It may be due to leaching of the more soluble constituents from the coin by solution in the soil, or to a very gradual migration of one constituent towards the surface. If the latter is the case, we might have an interesting method of dating ancient metallic objects. The problem will be tackled by taking cross-sections of the coins, analysing by the X-ray microprobe technique across the thickness of the metal, investigating how the composition varies with depth, and then comparing these 'composition contours' with the date of manufacture.

The analysis of glass and ceramics by wet methods presents an awkward problem to inorganic chemists. X-rays are especially useful in this field, since no solution of the specimen is necessary. Although many of the constituent elements occur in the 'vacuum spectrometer' region, this problem, as has been mentioned above, will be resolved when suitable equipment is available. Two examples, in the archaeological field, will suffice. The blue pigment in Chinese blue-and-white porcelain was made during early Ming times from imported cobalt ore which happened to be free from manganese. From the late Ming period onward, indigenous pigment containing a considerable percentage of manganese was used. Since eighteenth-century porcelain is hard to distinguish from early pieces, the presence of manganese found by non-destructive X-ray analysis can help in identification. Again, the presence of barium in large amounts in early glass is indicative of a Chinese origin, since Mediterranean glass appears to be free from that element.

Applications in the industrial field at the moment tend to be directed towards analysing alloys of high percentage composition or mixtures difficult to analyse by other means. Typical of the former are the estimations of copper and zinc in brass, of copper, zinc, and lead in powdered ore concentrates, and analysis of the Nimonic alloys. In the latter category the analysis of mixtures of the rare earths, of niobium and tantalum, of hafnium and zirconium, and of the platinum metals are cases where X-ray spectrometry is very superior to other methods of analysis.

The possibilities of the method in the analysis of solutions of very low concentration are little appreciated. For instance, as little as 10^{-8} g of many elements in solution, applied to a filter paper, will give an adequate response for purposes of identification, and in many instances less than one part per million in solution can be detected. Again, trace concentrations of the order of a few parts per million can be detected in light alloys, such as those of aluminium and beryllium, as can microgram quantities of uranium. Thus there are very many present uses of X-ray fluorescence, and no doubt in the near future we shall see a startling advance in the general application of this rapidly developing technique.

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The International Council of Scientific Unions

SIR HAROLD SPENCER JONES

The International Geophysical Year ended on 31st December 1958. This was the largest scheme of international co-operation in science that has ever been planned, and was organized by a special committee of the International Council of Scientific Unions. It was, however, only one of the achievements of the Council, and the origins, the activities, and some of the future programme of this non-political international scientific council are described in this article. The author was the Secretary-General of the Council from 1956 to 1958.

International co-operation in science was effected before the first world war through a heterogeneous collection of associations, each concerned with a very restricted domain of the various scientific disciplines. Most of these bodies had been established during the second half of the nineteenth century. Some of them were organized under inter-governmental diplomatic conventions, but many others were directly under German auspices and during the war became largely inactive. At a conference in London in October 1918 it was resolved that it was desirable that the nations at war with the Central Powers should withdraw from the existing conventions relating to international scientific associations as soon as circumstances permitted and that new associations, deemed to be useful to the progress of science and its applications, should be established without delay by the Allies, with the eventual co-operation of neutral nations.

The war ended in the following month, and the American scientist George Ellery Hale proposed that an international research council should be formed to establish new associations for co-ordinating international efforts in the different branches of science. On the joint initiative of the *Académie des Sciences*, Paris, the Royal Society of London, and the National Academy of Sciences, Washington, the International Research Council was founded in 1919. Its primary objects were to co-ordinate international efforts in the different branches of science and its applications, and to initiate the formation of international associations and unions deemed to be useful to the progress of science.

The Statutes of Scientific Unions formed under the aegis of the Council required the approval of the Council, and only allied and neutral nations were admitted to the International Research Council and the Unions. In 1919 the International Unions of Astronomy, of Geodesy and Geophysics, and of Chemistry were formed, and were followed in succeeding years by the International Unions of Scientific Radio, of Pure and Applied Physics, of Biological Sciences, and of Geography.

By 1925 the feeling had become rather general that international collaboration in science could not be fully effective while the Central Powers were excluded from membership of the Council and of the Scientific Unions. At the General Assembly of the IRC in that year a proposal was made by the Netherlands delegation that the Statutes should be modified to permit the Central Powers to be eligible for admission. This proposal was strongly supported by the delegations of Denmark, Sweden, the United Kingdom, and the United States, but did not receive a sufficient majority of votes for acceptance. At the same time the Unions were feeling that their activities and usefulness were being hampered by the restrictions placed upon them under the existing Statutes of the IRC.

As the Convention under which the International Council was constituted would have lapsed on 31st December 1931 unless previously renewed, the Royal Society of London proposed, at the General Assembly of the IRC in 1928, that a committee should be appointed to consider what changes, if any, should be introduced in the Statutes of the IRC and of its Unions, to take effect on the expiration of the Convention. The proposal was unanimously adopted and, as a result of the report of the committee, the International Research Council was reconstituted in 1931 as the International Council of Scientific Unions (ICSU), whose main purposes, according to the statutes then adopted, were to co-ordinate the national adhering organizations and also the various International Unions, and to direct scientific activity in

subjects for which there was no existing international association. At the same time each of the Unions was given complete autonomy in the management of its own affairs.

At the General Assembly of the ICSU in Copenhagen in 1949 various modifications to the Statutes were discussed, and at the General Assembly in Amsterdam in 1952 the present Statutes were adopted. The first of the Statutes states that the ICSU has two chief objects:

(*a*) to co-ordinate and facilitate the activities of the International Scientific Unions in the field of the Natural Sciences;

(*b*) to act as a co-ordinating centre for the National Organizations adhering to the Council.

Further objects of the Council are:

(*a*) to encourage international scientific activity in subjects which do not fall within the purview of any existing international organizations;

(*b*) to enter, through the National Adhering Organizations, into relations with the Governments of the countries adhering to the Council in order to promote scientific investigation in those countries;

(*c*) to maintain relations with the United Nations and its specialized agencies;

(*d*) to make such contacts and mutual arrangements as are deemed necessary with other International Councils or Unions, where common interests exist in the field of the Natural Sciences covered by the Council.

The Council has two categories of membership, national and scientific. National members adhere to the Council through a national organization, which may be either its principal scientific academy, or its national research council, or any other institution or association of institutions; or, failing these, the government. The scientific members of the Council are the Unions whose admission has been granted by the General Assembly. These Unions are now thirteen in number. In 1947 International Unions for Crystallography, and for Theoretical and Applied Mechanics, were accepted as scientific members, followed in 1952, by the International Union of Mathematics, in 1955, by the International Unions for Physiological Sciences and for Biochemistry, and in 1956, by the International Union for the History and Philosophy of Science.

The ICSU is administered by the General Assembly, which normally meets at three-yearly intervals, the Bureau, and the Executive Board. The General Assembly, to which the Bureau and the Executive Board are responsible, consists of the representatives of the national members and of the scientific members and elects the members of the Bureau. The Bureau is responsible for the general administration and meets at least once a year. The Executive Board consists of the members of the Bureau and of representatives of the scientific members and normally meets once each year.

The structure of the ICSU with its dual membership, national and scientific, which has developed from experience through the years in the organization of international co-operation in science, is of special interest. The ICSU is an international federation of Scientific Unions, each of which is completely autonomous in the management of its own affairs, and can admit national members, irrespective of whether they are members of the ICSU or not. The national members of the ICSU, at present 45 in number, help to guide the general policy of the Council through their representation at the General Assemblies of the ICSU, and have direct contact with the Unions through the National Committees. Each of the Unions has a National Committee in each of the countries that adheres to it. These National Committees may be formed under the national academy or research council which adheres to the ICSU, for example, in Great Britain under the Royal Society of London, in the United States under the National Academy of Sciences, or may be formed under a specialized scientific society as, for instance, in the International Astronomical Union, the National Committee for Astronomy for Germany is formed under the *Astronomische Gesellschaft*.

Unesco was formed in 1946 as one of the specialized Agencies of the United Nations. While ICSU is a non-governmental organization, Unesco is an inter-governmental organization, whose adherents are its member states. Unesco and ICSU have a number of overlapping interests and activities in the field of the natural sciences. A formal agreement was therefore drawn up between the two bodies in 1946, and this has been renewed yearly. Unesco recognizes that the International Scientific Unions provide a natural and appropriate means for the international organization of science, that the ICSU is the proper organism for representing them and co-ordinating their activities, and that the objects of the ICSU are in harmony with those of Unesco. The activities of the ICSU are in a field which is of interest to a large section of the programme of Unesco, so that the ICSU is in a position to provide an

important contribution towards the realization of the programme and objectives of Unesco.

Under this agreement Unesco provides an annual subvention to the ICSU to assist in the co-ordination of the activities of its members and to assist the financing of international scientific projects which are in accordance with the objectives of Unesco. Unesco is represented at the meetings of the Executive Board and General Assembly of the ICSU. The ICSU in return offers expert advice and counsel when called upon by Unesco. A provisional allocation of the Unesco subvention is made annually by a small committee set up by the ICSU for this purpose; each Union is then informed of this provisional allocation and may make suggestions for modifications or increases in the grants proposed. The allocation between ICSU and the Unions is further considered by the Bureau of ICSU and submitted to the Executive Board for approval or modification and for adoption.

There are various fields of interest shared between two or more Unions. In order to deal with these, Joint Commissions between two or more Unions have been formed where the need has been felt. These at present are five in number, namely the Joint Commissions on the Ionosphere, on Radio Meteorology, on Solar and Terrestrial Relationships, on Spectroscopy, and on Applied Radioactivity. The Joint Commission on the Ionosphere has representatives of the Unions of Radio Science, Astronomy, Geodesy and Geophysics, and Pure and Applied Physics. The Joint Commission on Radio Meteorology has representatives of the Unions of Radio Science, of Geodesy and Geophysics, and of Pure and Applied Physics. The Joint Commission on Solar and Terrestrial Relationships has representatives of the Unions of Astronomy, of Radio Science, and of Geodesy and Geophysics. The Joint Commission on Spectroscopy has representatives of the Unions of Pure and Applied Physics and of Astronomy. The Joint Commission on Radioactivity has representatives of the Unions of Chemistry, of Physics, of Biological Sciences, of Geodesy and Geophysics, of Biochemistry, and of Physiology. It may be mentioned that the first formal proposal for a third International Polar Year, not restricted to the Polar regions, came from the Brussels meeting of the Joint Commission on the Ionosphere in 1950.

Another activity of ICSU has been the formation of Special Committees to organize specific programmes of research in which international co-operation is necessary. There are at present three of these Special Committees, namely the Special Committee for the International Geophysical Year 1957–58, formed in 1953; the Special Committee on Oceanic Research, formed in 1957; and the Special Committee on Antarctic Research, formed in 1958.

The way in which the enterprise of the IGY was organized is of interest. The Special Committee, through a working group in each of the disciplines involved, first laid down the broad lines of the global problems for whose solution observations in all parts of the world were required. The National members of the ICSU and, also, countries not yet adhering to it, were asked to form National Committees to consider to what extent each country could contribute to the achievement of the objectives. From the National Reports and from subsequent meetings, negotiations, and proposals, the world-wide programme of simultaneous geophysical observations for 1957–58 was evolved. An Advisory Committee for the IGY, on which each participating country was represented, was formed to meet in conjunction with the Special Committee.

The enterprise of the IGY has proved to be by far the largest scheme of international co-operation in science that has ever been planned. Sixty-seven countries have co-operated in the programme, in which there have been more than 2000 observing stations well distributed over the whole earth. A special feature of the IGY has been the extensive use of instrumented rockets to obtain information about the upper levels of the atmosphere beyond those that can be reached by instrumented balloons, followed by the successful launching of instrumented earth satellites. The proposal that the launching of such satellites should be attempted originated with the Joint Commission on the Ionosphere and was supported by the Special Committee for the IGY.

Arrangements have been made for the storage of the vast mass of data obtained during the eighteen months of the observational programme at three World Data Centres, from which data can be obtained by scientific investigators who wish to use them.

Another special feature of the IGY programme has been the large programme of research in the Antarctic, a great and relatively unknown continent, which is of special significance to geophysics in many directions. During the IGY, 57 stations in the Antarctic were operated by 12 nations. As there was a widespread feeling that Antarctic research should not come to an end with the termination of the IGY, the ICSU has appointed a

Special Committee on Antarctic Research to organize the continuation of research in the Antarctic following the IGY, though necessarily on a somewhat reduced scale.

The observational programme of the IGY terminated on 31st December 1958, and consequent upon this, two further measures have been taken by the ICSU. In the first place there was a general feeling that the observational and data-collecting activities in the geophysical and related sciences should be continued after the end of the IGY. It has therefore been agreed that observations should be continued throughout 1959 at such a level and in such fields as may be determined by each National Committee. This extension of the IGY programme has been designated the International Geophysical Co-operation 1959. The second measure is concerned with the use and analysis of the data collected during the IGY. A Special Committee of the ICSU is formed to organize and carry through a specific programme of research. After the observations based on this programme have been completed the functions of the Special Committee come to an end. The exhaustion of the scientific content of the observational data is the responsibility of the Unions as the scientific members of the ICSU. The Special Committee for the IGY will therefore terminate its work on 1st July 1959, and the ICSU has appointed a Special Committee for Inter-Union Co-operation in Geophysics, whose task will be to deal with all aspects of the closing stages of the IGY enterprise, including the International Geophysical Co-operation 1959. Its activities will include publication, financing, and organization of international co-operation in the use and analysis of IGY data by the World Data Centres, the International Scientific Unions, the World Meteorological Organization, and otherwise.

The next large enterprise to be sponsored by the ICSU is in the marine sciences. Seven-tenths of the surface of the globe is covered by oceans, and the oceans present many problems that can be solved only by international co-operation. The ICSU therefore established in 1957 a Special Committee on Oceanic Research, representing an already existing organization, with the task of framing a programme of oceanic research; the countries that will collaborate in this programme will form National Committees to consider the contribution that they can make to the programme. The main fields of investigation have been considered in a preliminary manner by the Committee; it is planned that this programme should be implemented in the first instance with a survey of the Indian Ocean over a complete monsoon period in 1962–63. The Indian Ocean is the ocean about which least is known and, because of the two monsoon seasons, is the most suitable for certain fields of research. It is expected that at least twenty oceanographic research vessels will be in operation in the Indian Ocean during the period 1962–63. After the experience gained in this operation, it is probable that it will be continued in other ocean regions in later years.

The launching of instrumented earth satellites as a part of the IGY programme has opened a whole new era of space research. With the closing of the IGY the question arises whether international collaboration in space research should be continued under the auspices of the ICSU. Its national and scientific members were asked to give their views on the proposal that the ICSU should establish a committee on space research. The response was favourable, and the ICSU has appointed a committee on Space Research to function until the end of the year 1959. The primary purpose of this committee is to aid in the development of plans for space research on an international basis of free scientific activity. It will report to the ICSU the measures that are needed in the future to achieve the participation in international programmes of space research of all other countries of the world with those that are already actively engaged in research programmes involving the use of instrumented earth satellites and space probes. The Committee is instructed to keep itself fully informed on the activities of the United Nations and other international bodies in this field, in order to ensure that through such collaboration maximum advantage is accorded international space-science research.

Attempts to launch Moon probes have already commenced. Looking to landings on the Moon or planets in the foreseeable future, some scientists expressed concern lest such landings should be planned without adequate precautions to avoid undesirable contamination from terrestrial sources that might conceivably be prejudicial to certain lunar or planetary experiments of the utmost future interest and importance to science. This problem was brought before ICSU by a national member. The Bureau of ICSU appointed a Committee on Contamination by Extra-Terrestrial Exploration to specify conditions of landing that would keep contamination to acceptable levels. This Committee has produced an interesting report and has recommended that consideration

should be given to framing a specific code of conduct, which should achieve a reasonable compromise between the perfectly proper ambition to start lunar—and possibly planetary—exploration at the earliest moment, and the need to safeguard future research. The Committee has been instructed to draw up such a code of conduct and to report its conclusions to the Committee on Space Research.

Two further activities of the ICSU in the field of international collaboration in science must be mentioned. Following the Unesco meeting on Science Abstracting held in Paris in 1949, the ICSU, at its General Assembly in Copenhagen in that year, appointed a Joint Commission on Physics Abstracting. In September 1950 this Joint Commission took over complete responsibility for coordinating physics abstracting from Unesco, and in 1951 it was transformed into a Special Committee of ICSU, designated the ICSU Abstracting Board—IAB. This Board works with the cooperation of established abstracting journals admitted as member journals to the Board, and on the principle that in any particular branch of science there should be only one abstracting journal in each language. The prompt publication of abstracts in physics has already been efficiently organized, and the Board is now actively functioning to unify the abstracting services in the field of chemistry. At the request of the Biological Abstracting Services it is now studying the enormous field of biology to ascertain how it can effectively improve the heterogeneous state of abstracting in that science. An important adjunct to the work of the IAB is the appointment of correspondents in each country.

A second important activity of the ICSU is the Federation of Permanent Astronomical and Geophysical Services, which, after extensive negotiations with Unesco, was organized under Statutes accepted by ICSU in 1956. This Federation (FAGS) is concerned with the various Permanent Services associated with the Unions of Astronomy, of Geodesy and Geophysics, and of Scientific Radio. These Permanent Services, which were previously supported or maintained by the Unions, with in some cases national support, are the following:

International [illegible]e Bureau;
International Latitude Service;
Permanent Service of Geomagnetic Indices;
International Gravimetric Bureau;
International Seismological Summary;
Monthly Bulletin of the International Seismological Bureau;
International Commission on Atmospheric Ozone;
Quarterly Bulletin of Solar Activity;
Central Ursigram Service.[1]

The future of the International Bureau of Atmospheric Ozone is now under discussion with the World Meteorological Organization. To these Services has recently been added a World Mean Sea Level Service. A proposal was received by the ICSU that a Joint Commission on World Geophysical Days should be established to continue some of the work done under the IGY World Days Programme, including the advance specification of Regular World Days and World Meteorological Intervals in a World Geophysical Calendar; the specification of a current schedule of solar activity alerts; and the preparation of a post facto calendar of significant indices and outstanding solar and geophysical events.

The General Assembly of the ICSU, at its meeting in Washington in October 1958, approved that an International Service for World Days should be established as a permanent service under FAGS and delegated its authority in the formation and subsequent functioning of this service to the International Union for Radio Science.

FAGS has its own Council and is in receipt of subventions from Unesco and also from the ICSU. The allocation of these subventions is made after consideration of the needs of the various services, in conjunction with the support that they receive from national or other organizations. It has been emphasized by the ICSU that the purpose of these Permanent Services is to supply fundamental data of various sorts that are required in many geophysical investigations, but not to undertake scientific research.

The ICSU under its present statutes has assumed great responsibilities, and its activities have greatly expanded in recent years. As it is entirely nonpolitical, the organization of scientific affairs under its auspices is by scientists themselves, acting through their national academies and research councils. The ICSU is able to catalyse extensive research that would not otherwise be done. Through its special committees it can plan large programmes of research involving international collaboration, which are then organized through national machinery.

[1] A service for the transmission of coded ionospheric, solar, geomagnetic, and other geophysical data.

Hearing in whales

F. C. FRASER and P. E. PURVES

Cetaceans have been found to have a highly developed intelligence, but little has been known until recently about their sensory apparatus. Their sense of hearing is now known to be highly developed, and the modifications that have occurred to the terrestrial mammalian ear in order to fit it for use under aquatic conditions are described in this article.

Cetaceans are mammals that have an exclusively aquatic mode of life. They are born, feed, move, and reproduce in the water. Until cetaceans were kept for more or less protracted periods in captivity little was known about their behaviour. Observation and experiment, mainly at Marineland, Florida, have shown that the dolphins kept there have a very high level of intelligence. 'In respect to emotional and motivational behaviour, the dolphin appears to fall somewhere in the range of development of dog and chimpanzee' [1].

It would be expected that the long-range sense receptors of the cetacean would be at least as highly developed as those of the higher terrestrial mammals. Cetaceans are almost or altogether without the sense of smell. In the baleen whales there are only reduced olfactory organs, while in the toothed whales not only are they absent but the olfactory lobes of the brain are completely atrophied.

There is evidence that the visual sense can be normally developed and adapted to underwater vision in conditions of good visibility, but there must be conditions of turbidity or depth in which the eyes cannot function. The first of these factors operates particularly among the primitive river dolphins, and it is significant that the eyes of these animals are very much reduced in size.

Experiments have, in fact, shown that in cetaceans the most discriminating of all the long-range perceptors is the sense of hearing. The lack of visible external ears and the extremely small calibre of the external auditory meatus have led many anatomists to the conclusion that some method of hearing other than that normal to terrestrial mammals must be involved. One of the reasons for this conclusion is that the whole approach to an interpretation of cetacean hearing has been conditioned by the anatomical and physical factors involved in human hearing.

The human ear (figure 1), in common with the ears of all terrestrial mammals, contains a mechanism for converting the relatively large displacement amplitudes of the air-borne waves received by the eardrum to movements that can be detected by the hair cells of the cochlea. The contents of the cochlea are almost entirely fluid, so that its acoustical properties approximate to those of water. Sound waves in air normally suffer displacement amplitude loss in passing into such a medium—and without the middle-ear mechanism there would be no displacement of the hair cells relative to surrounding structures and there would be no sensation of hearing.

Figures 1 and 2*a* shows the mechanism diagrammatically; the effect of the bony levers added to that of the difference in area between the eardrum and the stapes gives a sixty-fold increase in pressure at the fenestra ovalis,[1] corresponding to the sixty-fold increase in the pressure amplitude of a sound wave in water compared with that of a sound wave of the same frequency and intensity in air.

Anatomical investigations [2] have shown that, while the cetacean ear retains the essential mammalian components, they have been modified to function in the different physical conditions involved in the aquatic mode of life. The cochlea, apart from the ability to respond to ultrasonic frequencies, is similar to that of terrestrial animals, and it is the middle-ear mechanism that shows the modifications necessitated by the fact that the sound waves reaching the whale's ear are travelling through water. This mechanism must produce an increase in the displacement amplitude of the vibration while the relative areas of the structures must be such as to maintain the pressure amplitude at the same level as that in the surrounding water.

Figure 5 shows a dissection of the squamomastoid region of the head of a fin whale. Starting from the right, there can be seen the small aperture of the meatus penetrating the blubber. The aperture is about the diameter of a lead pencil

[1] This ratio is not accepted by all human anatomists, but in view of the physical properties of sound conduction in water we consider the figures quoted to be the more accurate. The evolutionary implications are of extreme importance.

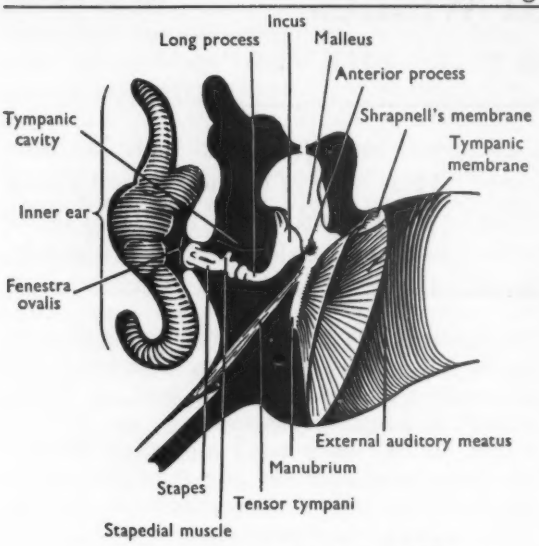

FIGURE 1 – *Diagram of the human middle ear.*

and is lined with black epithelium which is continuous with that of the external skin. The cartilages of the external ear and its related muscles are present, and are apparently functional although situated below the surface of the blubber. Thereafter the meatus is reduced for a distance of about six inches to a tightly stretched cord which lies in a groove in the mastoid. Further towards the tympanum the cord formed by the meatal corium develops into a tube filled by a dense mass of horny epithelium, referred to as the ear plug. At the tympanum this plug invests a structure resembling the finger of a glove, the homologue, in human anatomy, of Shrapnell's membrane (figure 1). In the toothed whales, with the possible exception of the sperm whale, the external meatus is open throughout its length, but it is much narrower, and is traceable in the dissected specimen as a thin black pigmented tube no more than a millimetre or so in diameter. In the dissection shown in the plate, half of the massive tympanic bulla has been removed to expose the middle-ear cavity with its associated air sinus. Figure 3 shows the middle ear and cochlea (C) of a fin whale and will be described with reference to figure 1, a diagram of the human ear. In the dissected whale's ear the tympanic bulla which forms the floor of the tympanum has been cut away to expose the auditory ossicles (M, ST), muscles, and other ear structures. The tympanic membrane of the human ear is a circular membrane slightly concave mesially, attached around its circumference to the tympanic annulus and, internally, to the handle of the malleus. The axis of vibration of the membrane lies at right angles to that of the manubrium of the malleus (see figure 2*a*). Shrapnell's membrane (GL) in the whale has become grossly enlarged to form the glove-finger. The tympanic membrane, extended and folded like a closed umbrella (see also figure 2*b*), forms what will subsequently be referred to as the tympanic ligament (TL). In the same process the manubrium of the malleus has become extremely shortened and thickened and the axis of longitudinal vibration of the tympanic ligament lies almost parallel with it—not at right angles as in terrestrial mammals. The anterior process (processus gracilis) of the cetacean malleus is greatly enlarged and of channel-girder construction. A junction of extremely thin bone along its lateral margin fuses the processus gracilis to the tympanic bulla. This edge of the anterior process is buttressed by a stout projection of the tympanic annulus—the sigmoid process (SP). In the cetacean the long process of the incus is also

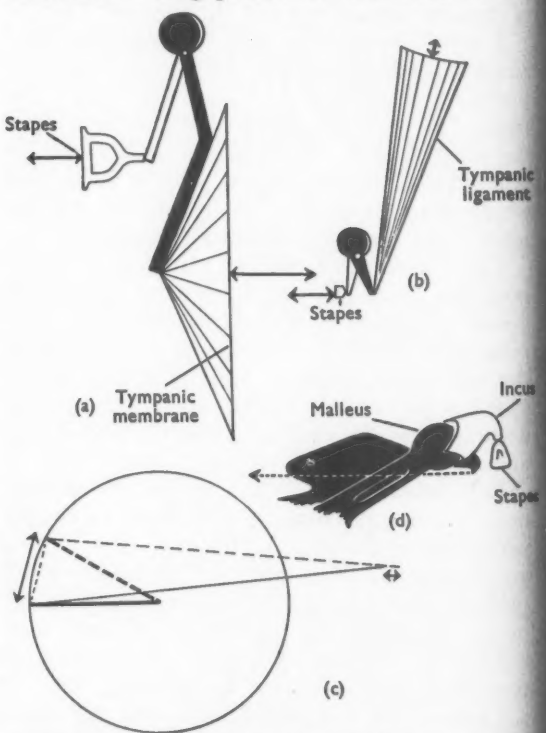

FIGURE 2 – *Schematic drawing of mode of operation of human and cetacean tympanic membrane and auditory ossicles. (a) Human ear drum and ossicles. (b) Cetacean ear drum (tympanic ligament) and ossicles. (c) Crank action of tympanic ligament of cetacean. (d) Angular articulation of malleus and incus in the cetacean. The dotted line shows line of traction of the tympanic ligament. (By permission of the Trustees of the British Museum.)*

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FIGURE 3 – *Middle ear and cochlea of fin whale. Note tympanic ligament (TL) attached to manubrium mallei (MM), processus gracilis fused to the bulla and sigmoid process (SP), the tensor tympani lying to the right, and carotid artery to the left of the cochlea (C); the incus (I) is visible to the left of the tympanic ligament, the muscle of the stapes (ST) lying in a groove above the latter. Note also the muscle mass (M), the tendon of which passes through the tympanic annulus to the internal face of the glove-finger (Shrapnell's membrane, GL).*

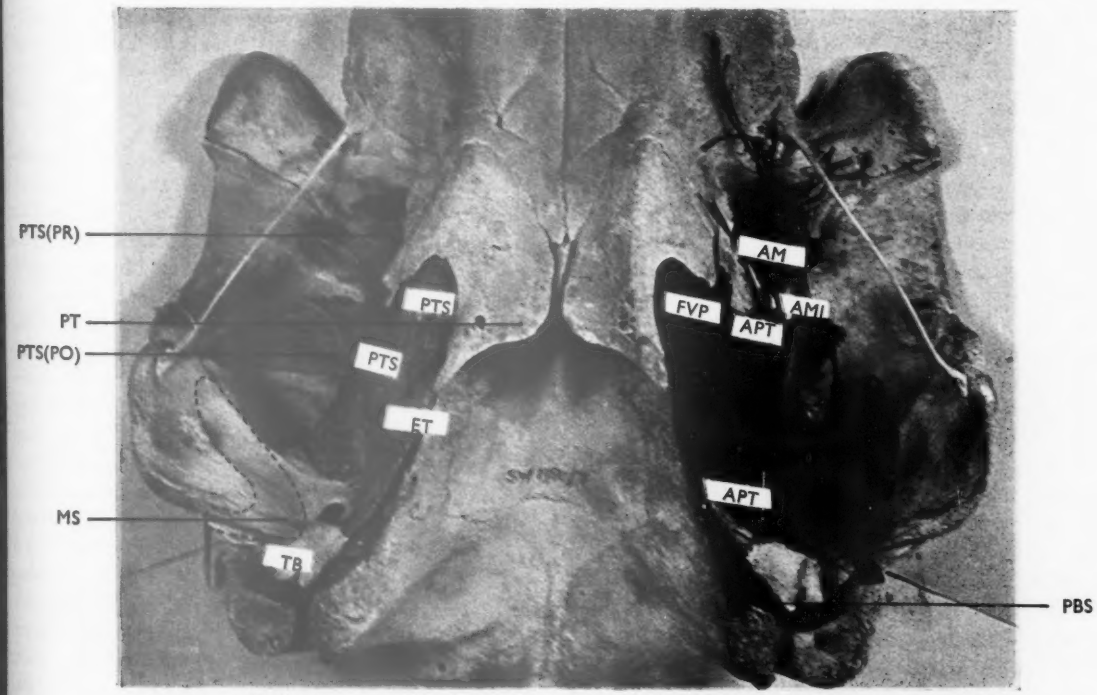


FIGURE 4 – *Skull of a young pilot whale in which the air sinus system and its vascular network have been injected with polyester resin.*

AM Mandibular artery
AMI Internal maxillary artery
APT Pterygoid artery and arterial branches to internal pterygoid muscle
ET Eustachian tube
FVP Fibro-venous plexus
MS Middle sinus
PBS Peribullary sinus
PT Pterygoid bone
PTS Pterygoid sinus
PTS(PR) Preorbital lobe of pterygoid sinus
PTS(PO) Postorbital lobe of pterygoid sinus
TB Tympanic bulla

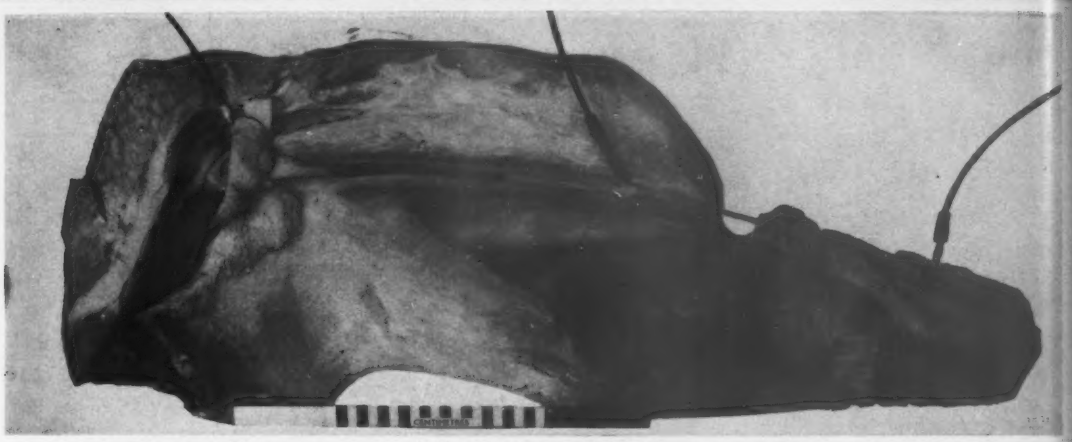
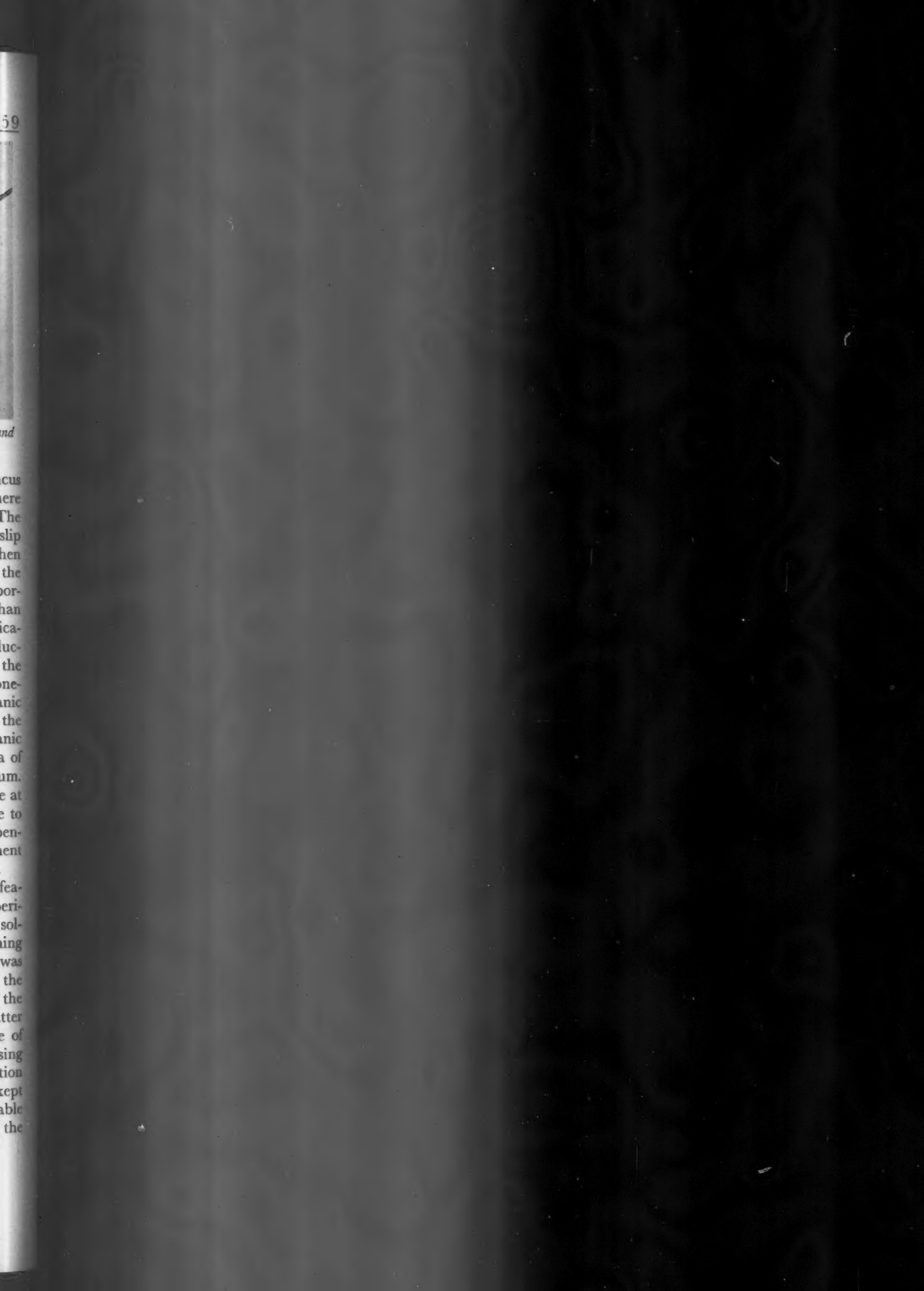


FIGURE 5 – *Dissection of the external and middle ear of a fin whale (ventral view). The probes used for testing sound conductivity are shown in situ.*

considerably shortened as compared with that in man. Quoting from Gray's 'Human Anatomy': 'The handle of the malleus follows all the movements of the tympanic membrane while the malleus and incus rotate together about an axis which runs through the short process of the incus and the anterior ligament (and therefore the processus gracilis) of the malleus. When the tympanic membrane and handle of the malleus move inwards the long process of the incus also moves in the same direction and pushes the base of the stapes towards the labyrinth' [3]. A mechanical study of the ossicles shows that this description is true also for cetaceans, with one important difference. In these the tympanic ligament is attached only to a point at the tip of the manubrium of the malleus, making a sharp angle with the latter in the manner referred to above. In these conditions the ligament acts like a piston rod attached to a crank, so that any small movement of the meatal end of the ligament produces a relatively large movement of the tip of the manubrium and therefore of the tip of the long process of the incus (figure 2*c*). Experimental evidence has shown that this amplification is in the region of 30 : 1, as compared with the approximately 2 : 1 reduction in the human ear.

In order that this amplification should be produced, the effective movement of the malleus must be solely rotational, and this is achieved by the stout channel-girder construction of the processus gracilis and its mode of fusion to the tympanic ring. The buttressing effect of the sigmoid process ensures that lateral movement of the malleus by the ligament is obviated and that the processus gracilis is capable of torsional vibration only. The angular articulation of the malleus with the incus (figure 2*d*) produces a condition in which there is positive oscillatory drive by rotation only. The smooth, curved surfaces of the facets tend to slip over one another in one or both directions when the oscillation is longitudinal, or transverse to the processus gracilis. This factor is of great importance in the exclusion of vibrations other than those of the tympanic ligament. The amplification described above involves a thirty-fold reduction of power. In order to compensate for this, the foot of the stapes has an area approximately one-thirtieth of that of the distal end of the tympanic ligament. The ratio of the area of the foot of the stapes to that of the distal end of the tympanic ligament is thus equal to the ratio of the area of the foot of human stapes to that of the eardrum. Whereas in man the resultant pressure increase at the stapes compensates for the power loss due to the gaseous environment, in cetaceans it compensates for the power loss due to the displacement amplitude produced by the ossicular leverage.

In order to demonstrate the amplification feature of the cetacean malleus the following experiment was performed. A thin steel wire was soldered to one end of a conical transducer containing a barium titanate ceramic, and the other end was attached to the tip of the manubrium of the malleus at the normal point of attachment of the tympanic ligament, so that it simulated the latter in length and position (figure 6). The angle of attachment of the wire could be altered by raising or lowering the transducer relative to the position of the manubrium, while the tension was kept constant by attaching a small weight to the cable which ran over a pulley and connected the



variable-frequency oscillator and transducer. The incus was allowed to rest on the malleus in its natural position, separated from it by a thin film of petroleum jelly. The stapes was simulated by the stylus of a microgroove crystal pick-up which was connected to an amplifier and cathode-ray oscilloscope. The frequencies used in this experiment lay between 10 and 100 kc/sec. A considerable difference was noted in the height of the deflection of the time base in relation to the angle which the wire made with the long axis of the manubrium mallei. When the wire was pulling at a sharp angle, one of approximately 5°, the deflection was about ten times the height attained when the wire was pulling at right angles to the manubrial axis. With the wire pulling at right angles to the manubrium the ratio between the displacement amplitude of the crystal face and that of the tip of the manubrium would be unity, and it would increase as the angle of attachment of the wire diminished, until it approached infinity with the wire almost parallel to the axis of the manubrium. This method of amplification is to some degree self-compensating, since the smaller the displacement amplitude of the sound wave the greater the relative amplification.

ADAPTATION FOR DIRECTIONAL HEARING

Directionality is probably the most important of the attributes of hearing to animals in general. In terrestrial mammals, because of the difference in physical properties between the body tissues and the ambient air, the greater part of the sound energy impinging on the head is dissipated, only the part that is received at the external ear being transmitted to the cochlea. Mobility of the head, movements of the external ears, and their degree of separation, all provide differences of intensity, quality, time, and phase between the ears as factors in directional hearing. In cetaceans, because of the relatively close similarity between the acoustical properties of their body tissues and water, nearly all the sound energy impinging on the body is transmitted. To achieve the separation of the ears required for directionality, therefore, acoustic isolation of the two cochlea from the

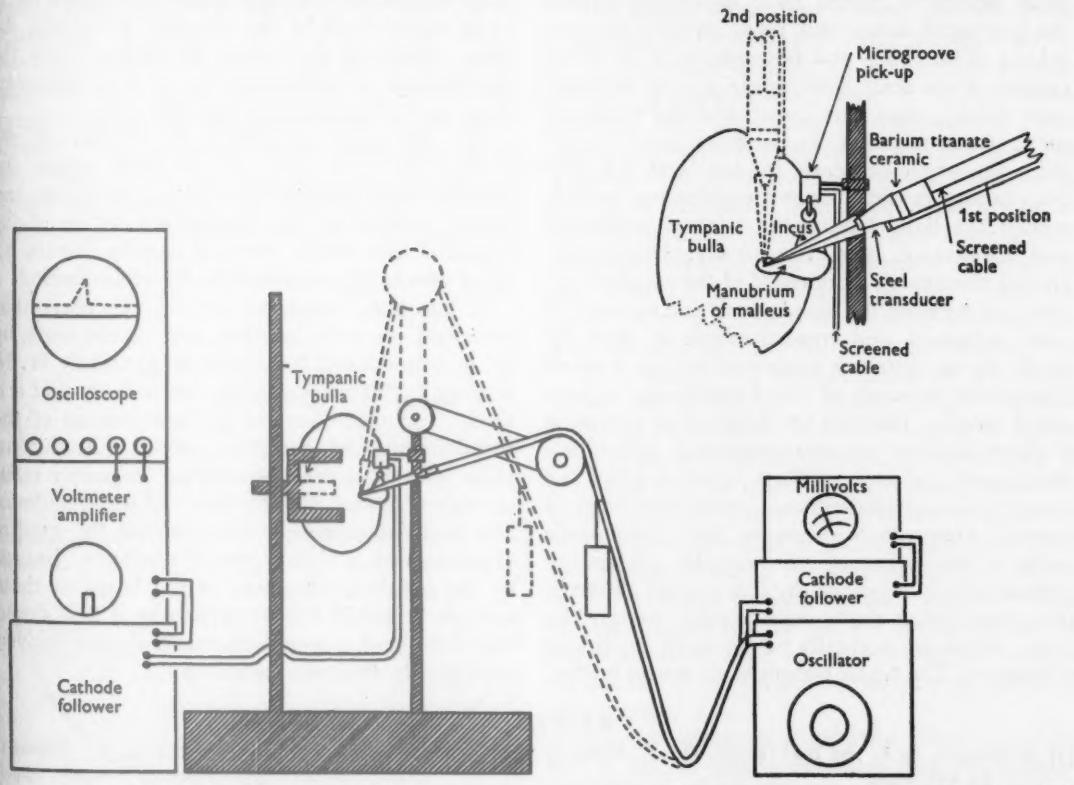


FIGURE 6 – *Apparatus for demonstrating changes in the amplitude of torsional oscillations of the malleus when actuated by a simulated tympanic ligament vibrating longitudinally at various frequencies and angles of traction.* (*By permission of the Trustees of the British Museum.*)

rest of the body is essential. It is believed that the auricular muscles, those of the sinus system, and the sinus system itself are brought into operation for appreciation of intensity and quality differences. Because of the greatly increased velocity of sound in water, and its reduced attenuation, directional hearing also involves increasing the range of sensitivity of the ear to accommodate high-pitched and ultrasonic frequencies, the wavelengths of which are small compared with the linear dimension of the head.

During the evolution of the cetacea from their terrestrial ancestors the tympano-periotic (TB, figure 4) has become completely dissociated from adjacent bones of the skull. Moreover, the bones surrounding the periotic have been excavated and eroded by pneumatized extensions of the middle-ear cavity so that the periotic is enveloped in a system of air-filled sacs (PBS). Anteriorly to the periotic, the extension of the middle-ear cavity has split each pterygoid bone into two laminae, which in many species have become widely separated. The extensions in the more advanced species have developed beyond the pterygoid bones and have invaded the preorbital (PTS (PR)) and post-orbital (PTS (PO)) regions of the skull base (figure 4). In the common dolphin they have penetrated the elongated snout almost to its tip. In the more primitive dolphins the whole or nearly the whole of the outer bony lamina persists, but as specialization has proceeded the bony lamina has become perforated and fenestrated, and has finally disappeared. During the process of removal of the calcified elements of the bone, the blood vessels and periosteum have remained and hypertrophied so that the whole air sac system is contained within a tough fibro-elastic network of blood vessels and a periosteal sheath. The sacs are lined by an extension of the middle-ear mucous membrane with abundant glands and mucous ducts, between which is a layer of ciliated epithelium. Under conditions of normal atmospheric pressure the fibro-elastic walls of the veins of the vascular plexus are pressed closely together, in this respect differing from non-fibrous elastic veins in other parts of the body, which are normally turgid at all conditions of pressure. The whole system of air spaces is filled up by an extremely stable foam, the liquid phase of which is a finely divided mucus–oil emulsion secreted by the mucous membrane that is present as a lining. With the increased hydrostatic pressure involved in diving, the sinus spaces are diminished in volume and the evacuated space is filled by injection of blood into the vessels of the fibrovenous plexus (FVP). By this process, equilibrium is maintained between the gaseous pressure in the tympanic cavity and the hydrostatic pressure external to the tympanic ligament. By the same process an air envelope is maintained round the periotic, for acoustic isolation, and round the auditory ossicles and fenestra rotunda to allow for the displacement amplitudes previously described.

The efficiency of such a layer was tested experimentally. A similar type of foam was compressed to 100 atmospheres and observed through an optical cell. The bubbles were greatly diminished in volume but were still observable after 20 minutes at this pressure. This implies that a residual film of air would persist throughout the sinus system at all conditions of pressure likely to be experienced by the cetacean, providing the ideal conditions for sound dissipation, with the implications of differences of quality, intensity, time, and phase between the two ears.

The foregoing simplified description of the system does not take into account either the voluntary functioning of auricular, pterygoid, and palatal muscles or the involuntary action of the stapedial and tensor tympani muscles (figure 3), all of which are important in direction-finding.

It has been suspected for several years that cetaceans use echo location, and recent work by W. E. Schevill and B. Lawrence [4] and by W. N. Kellogg [5] have established conclusively that it is used. The echo-location method consists of the transmission and reception of an intermittent pulse with a variable recurrence frequency comparable with that used by bats. There is evidence also that cetaceans can discriminate the quality of echoes with a high degree of accuracy. Judged by the great development of the brain of these animals it would not be surprising if it is found that they have a complete sound picture derived from purely auditory sensations.

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The interior of the Earth as revealed by earthquakes

I. LEHMANN

The study of seismic waves resulting from earthquakes has long been a means of investigating the inner structure of the Earth. Recent improvements in recording instruments and in methods of analysing results obtained by them have added considerably to knowledge in this field, although much still remains to be done. Analysis of the waves resulting from atomic explosions offers a new way of progress, of which some advantage has lately been taken.

The deep interior of the Earth is inaccessible, and no rays of light penetrate to let us see what is below the surface. But rays of another kind penetrate and carry with them their messages from the interior. The Earth has been found to have elastic properties that allow movement set up at the source (focus) of an earthquake to radiate into the interior and to spread over the surface. In a strong earthquake the whole of the Earth is set vibrating. At some distance from the focus, depending on the strength of the shock, the movement is no longer perceptible, but sensitive seismographs can record the waves that emerge at the surface. The records provide data from which knowledge of the Earth's interior may be gained. From seismic studies we have learned that the Earth consists of a core surrounded by a mantle on which there is a crust; inside the core there is a small inner core (figure 1).

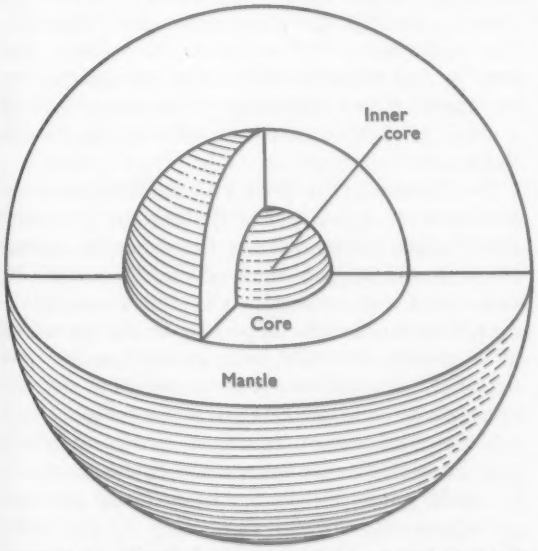

FIGURE 1 – *Diagram showing mantle, core, and inner core of the Earth.*

Towards the end of the nineteenth century it was realized that earthquake movements extend to great distances from the focus. Systematic recording of earthquakes began, and the very important results gained at an early stage greatly stimulated interest in this new science.

The elastic waves that radiate into the Earth are of two kinds, having different speeds of travel: P waves (*undae primae*), in which the particle motion is longitudinal, and S waves (*undae secundae*) with transverse particle motion. The speed of S waves is roughly 60 per cent of that of P waves. The arrivals of the waves are marked by groups of oscillations in the seismograms, and at moderate distances from the focus they usually stand out clearly. The seismogram of figure 2 was obtained at a distance of 18·6° from the focus.[1] P and S appear on it. The large oscillations succeeding S are due to surface waves.

We measure the arrival times of the waves today usually with an accuracy of not less than 1 second, and deduce the travel times of the waves from focus to recording station, if the location of the focus and the time of occurrence of the earthquake can be found. When a fair number of travel times to points at different distances from foci at approximately the same depth (the normal depth is about 10–20 km) are available, time-distance tables can be set up, giving the travel times of each type of wave over the various distances. It is customary to present them as time-curves.

The first attempts to construct time-curves for the P and S phases revealed that the average

[1] Distances in seismology are angular distances subtended at the centre of the Earth, as a first approximation taken to be a sphere.

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speed, as determined along the chords, increased with focal distance, indicating that the wave velocity increased with depth. As a consequence of this the rays are not straight lines but have an upward curvature.

At about 100° focal distance P and S became small and at somewhat greater distances could not be detected. Clear P phases reappeared at about 140°, but they had been delayed, so that their travel times did not fit on to the continuation of the time-curve for shorter distances. This observation was made in 1906 by R. D. Oldham, who drew the conclusion that deep in the Earth there was a decrease of velocity, causing the rays to bend downwards so as to leave part of the Earth's surface in shadow. He attempted to calculate the depth at which the decrease of velocity occurred, but his observations were not good enough for this purpose; therefore his results were very much in error. E. Wiechert, in Göttingen, had also come to the conclusion that the Earth had a core in which the velocity was smaller than in the surrounding mantle. It was the first great achievement of B. Gutenberg to establish this beyond doubt by means of records of distant earthquakes obtained on the Wiechert seismographs at Göttingen, and to calculate the radius of the core. His result did not differ much from later ones obtained from modern and more abundant data.

Gutenberg made use of the time-curves for P and S up to about 103° established by Wiechert and Zöppritz, and of the wave velocities derived from them. At that time formulae had been developed by means of which transmission times to different distances could be calculated when the velocity as a function of the distance from the Earth's centre was known, and also formulae by means of which the wave velocities as a function of depth could be obtained when the time-curve was known. The ray emerging at the distance where the P curve broke off would graze the core.

The belated P waves observed from a little beyond 140° onwards had passed through the core, but the velocity of these waves in the core could not be derived from the formulae used for the mantle, for these formulae break down when there is a discontinuous decrease of velocity, as at the core boundary. But when a velocity distribution in the core was assumed the travel times could be calculated and Gutenberg varied his assumptions until the calculated travel times agreed with those observed. The velocity as a function of depth was then known for the whole of the Earth to a first approximation.

On theoretical grounds it was to be expected that the rays would be reflected on reaching the surface of the Earth and would be reflected and refracted at discontinuity surfaces in the interior, such as the boundary of the core, partly as rays of the same kind and partly transformed into rays of the other kind (P into S and vice versa). Thus at great distances from the epicentre (the point on the Earth's surface directly above the focus) waves would be arriving along many different paths, producing oscillations in a seismogram and marking phases more or less prominent according to the energy carried. When the velocity distribution within the Earth is known, it is possible to calculate the transmission times along all the different paths.

When earthquake records are examined a great many of the anticipated phases can be identified, but some of those originally expected to be present are not found, namely all those that would have come as S waves through the core. Since phases may be present without being very clear, many years passed before it was definitely concluded that transverse waves were not transmitted through the core. At the surface of the Earth a fluid does not transmit transverse waves, and therefore we say that the core is fluid, although in other respects it may not resemble a fluid as we know it.

The shadow zone for the P phase extends from about 105° to 143° epicentral distance. With modern highly sensitive instruments the P phase is found not to be completely absent in this range: in strong earthquakes it is usually faintly recorded. The appearance of P waves in the shadow zone may be due either to diffraction around the core boundary or to a spreading of the rays caused by a small gradual decrease of velocity just outside the core.

In addition to this faint P phase there is, in the shadow zone, another later P phase that is faint at the smaller distances. On Gutenberg's original Earth model its presence could not be explained, and it was vaguely ascribed to diffraction. However, as seismographs improved it was more and more clearly recorded, and an explanation was required. In 1936 the writer pointed out that the presence of a small inner core in which the P velocity was greater than just outside it would fully account for the occurrence of the phase, for it would cause incident rays to bend upwards strongly enough for part of them to emerge in the shadow zone. Gutenberg and Richter accepted the existence of this inner core and calculated its

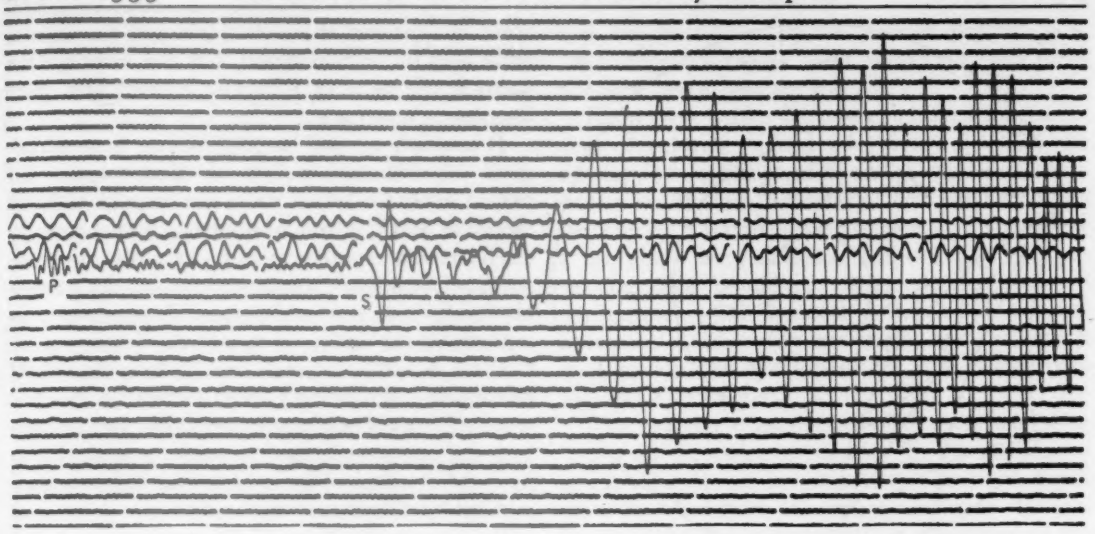

FIGURE 2 – *The earthquake of 23rd July 1929 recorded at Copenhagen at epicentral distance 18·6°.*

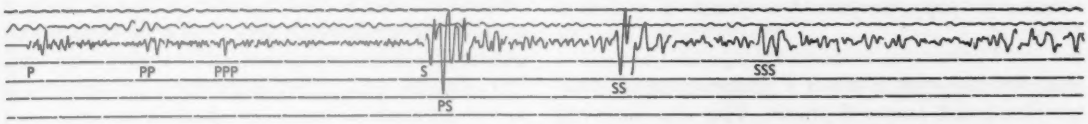

FIGURE 3 – *The earthquake of 30th June 1936 east of Kamchatka recorded at Copenhagen at epicentral distance 70·1°.*

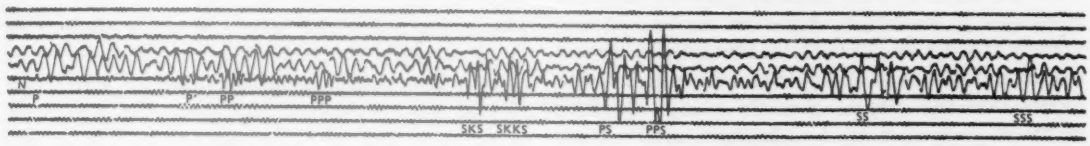

FIGURE 4 – *The earthquake of 1st March 1948 off the west coast of New Guinea recorded at Scoresby-Sund at epicentral distance 108°.*

radius and the velocity distribution in it. Later H. Jeffreys proved that diffraction could not account for the phase in question.

Figure 3 is part of a seismogram recorded at an epicentral distance of 70·1°. PP, SS and PPP, SSS are, respectively, phases due to waves reflected once and twice at the surface of the Earth. PS starts as P and is reflected as S.

Figure 4 is part of a seismogram recorded at an epicentral distance of 108°. P′ is here the P wave reflected at the boundary of the inner core. SKS starts as an S wave, traverses the core as a P wave, and is again an S wave after leaving the core. SKKS is also an S wave outside the core and a P wave inside, but it is reflected when, from inside, it meets the core boundary. Figure 5 shows the paths of the rays corresponding to some of the phases of figure 4.

In figure 6 are seen the time-curves of the phases already mentioned and of a few others. PKP is the same phase as P′. A great many more phases occur, especially at great epicentral distances.

The fact that on the mantle there is a crust differing distinctly from it was shown by A. Mohorovičić in 1909; the boundary between crust and mantle is called the Mohorovičić discontinuity. The wave velocity in the crust is smaller than in the mantle underneath, and therefore the waves coming through the crust are refracted and bent upwards when they meet the mantle. There will be a range of distance within which both the refracted and the direct waves emerge, as indicated in figure 7; at a certain distance the refracted wave overtakes the direct wave because it travels faster in the lower layer. But its path is longer, and energy is lost on refraction, and therefore the corresponding phase in a seismogram will be smaller than that due to the direct wave. There

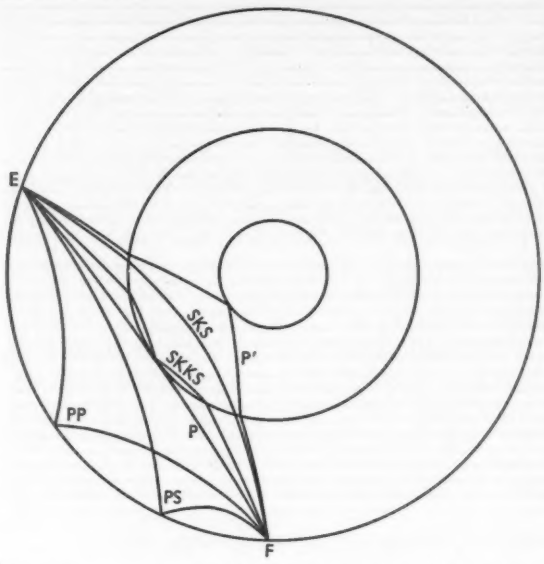

FIGURE 5 – *Rays from focus F to epicentre E at distance* 108°.

therefore appears a small P phase succeeded by another much larger P phase. This was observed by Mohorovičić, who gave the correct interpretation. He was interested in finding the depth of the discontinuity but did not have the means of determining it with any accuracy. Actually it turned out to be extremely difficult to arrive at reliable values for the depth, though many different methods were employed. The best results have been obtained from explosions, which can be looked upon as artificial earthquakes. They can be timed with great precision, and the focus is exactly known; when they are well recorded at suitable distances more useful data are obtained than can be derived from earthquakes. It now seems to be established that the discontinuity is at a depth of between 30 and 40 km under most continental areas. Under the deep oceans it is at a much smaller depth, only about 10–15 km under the water surface.

While the evidence for the existence of the Mohorovičić discontinuity and of the other subdivisions of the Earth mentioned above is very clear, precise determination of their depths is difficult. It depends on very precise determination of the velocity variation throughout the Earth, and this in turn depends on precise determination of the travel times of the direct P and S waves and of some of the reflected and refracted waves. Much important work has been done along these lines, a great deal of it in the 1930s. In the course of this work it appeared that subdivisions of the mantle have also to be considered, but the evidence for them is not of a very precise nature, and their location is uncertain.

It is a difficult and lengthy process to construct good time-distance tables or time-curves. To obtain accurate travel times we require to have the focus and the time of occurrence of the earthquake accurately determined. As a rule this cannot be done directly, because there are not enough observations close to and around the epicentre. It is therefore necessary to make use of time-curves already in existence, and there is then the risk of transferring errors from these curves to the new travel times. When time-curves have been determined from them it may therefore be desirable to have the elements of the earthquakes redetermined and the whole process repeated.

For the construction of the time-curves it has been customary to use a graphical method, plotting travel times against distance and drawing a smooth curve through the cluster of points thus obtained. It is a somewhat arbitrary process, and, in common with other smoothing procedures, it is apt to smooth away or faultily to introduce changes of slope or curvature. This is serious,

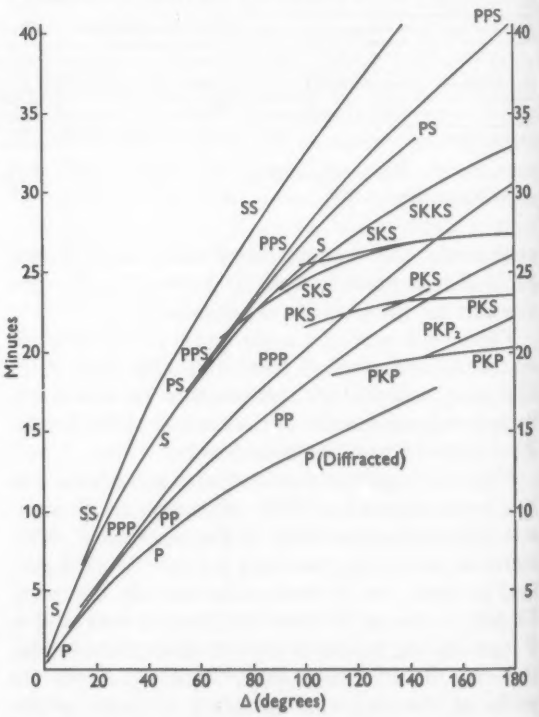

FIGURE 6 – *Travel times for a surface focus (Jeffreys-Bullen,* 1940).

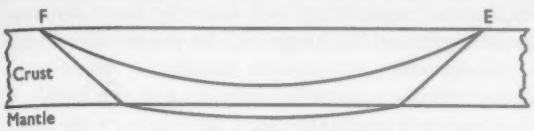

FIGURE 7 – *Direct and refracted rays from focus F to epicentre E.*

because it is such changes that indicate the existence of more or less abrupt changes of velocity or velocity gradient in the Earth. Many time-curves have been constructed in the course of time, and the existence of various so-called discontinuities has been derived from them.

Two sets of time-distance tables or time-curves are now available which are far better than any previous ones. They are due to Gutenberg and Richter and to Jeffreys and Bullen. In 1928 Gutenberg published his *FrankfurterLaufzeitkurven* based on a large number of observations. In collaboration with C. F. Richter he greatly extended the work. In 1936 they jointly published the first part of 'On seismic Waves', containing time-curves for a great many phases. Amplitude variation was considered for the fixing of the distances at which the curvature of the time-curve was either greater or smaller than usual. The amplitudes of the recorded waves should be relatively large at the distances where the time-curve bends strongly, and amplitudes should be small where the curve is straight. Amplitudes were measured and used, and although very precise information is not derivable in this way, some useful indications were obtained.

The readings of the seismic records from all over the world are collected and published in 'The International Seismological Summary' (I.S.S.), for which foci and times of origin of individual earthquakes are determined. For the reduction of the data down to 1928 inclusive the Zöppritz tables were used, but it became more and more apparent that the times given by these tables departed seriously from actual travel times.

In 1928 Jeffreys began his very important work on travel times by a preliminary revision of the Zöppritz tables, using I.S.S. data. Later he undertook a thorough revision in collaboration with K. E. Bullen. A great quantity of data was used, and for the first time statistical methods were applied and the accuracy of the results obtained was evaluated. This implied difficult and extensive work because of the complicated processes involved. In part, new methods had to be developed. After the main work many special investigations followed, improving somewhat the first results. In 1940 the Jeffreys-Bullen (J-B) 'Seismological Tables' were published, and these are now being used for the I.S.S.

From these tables Jeffreys calculated the variation of velocity with depth (figure 8). On the whole, the velocities of P and S waves increase down to the core boundary. Jeffreys found the velocity of P waves to be 5·6 km/sec in the upper crust, below the sediments, and to be 13·6 km/sec at the core boundary, where it decreases to 8·1 km/sec. With increasing depth the velocity increases steadily in the outer core to about 10·4 km/sec. In the inner core it is nearly constant at 11·2 km/sec.

The velocity does not increase uniformly with depth all through the mantle. In the uppermost mantle the velocity increases slowly, but at a depth of a few hundred kilometres a strong velocity increase sets in, as indicated by a bending of the time-curve around 20° epicentral distance. Below a depth of about 1000 km the velocity again increases more slowly.

On the whole, the velocities as derived from the Jeffreys-Bullen tables are probably not far wrong, but there are serious uncertainties. This is chiefly because it is so difficult to determine the slope of the time-curve accurately. The boundaries of the mantle regions in which the velocity gradients differ are indicated by changes of slope and curvature of the time-curve, but our data are not accurate enough for us to say exactly where these occur. It has been found particularly difficult to determine the velocity variation near the boundary of the inner core.

A vast amount of data, in part more reliable, has accumulated since Jeffreys and Bullen constructed their tables. New seismographs have been developed, from the records of which the arrival

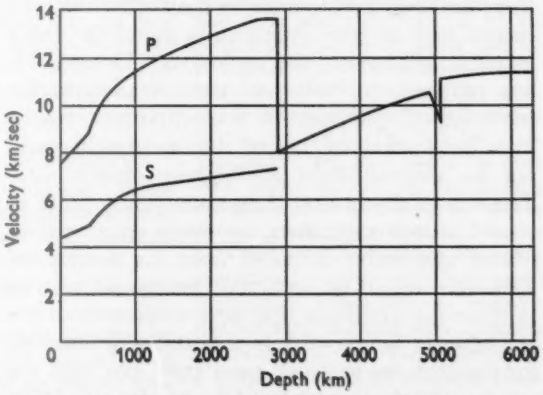

FIGURE 8 – *Velocity as function of depth according to H. Jeffreys*, 1939.

times of the phases can be read with greater precision. In addition, explosion work has entered the picture. It has for a great many years been used for the exploration of the crust, especially for the finding of oil; since the second World War more effective explosives have been available, and many of the explosions have yielded results also for the upper mantle. Some large accidental explosions have also provided seismologists with new data. It was then found that the velocity just below the crust was greater than that derived from the Jeffreys-Bullen tables. Jeffreys drew attention to this, and in later work he provided corrected P tables for distances up to 30° for Europe. For, to complicate matters, it turned out that there were regional differences not only in the crust but also in the uppermost mantle. From the new tables it appears that the strong increase of velocity gradient in the mantle at first placed near 400 km depth is likely to occur at a much smaller depth, probably between 200 and 250 km. However, attempts to fix the depth accurately have as yet met with unsurmountable difficulties.

The study of the Earth's interior is approached from many different directions. The upper mantle plays an important part in many investigations, and geophysicists in various fields look to seismologists for precise and detailed information. Have we any means of supplying such information?

K. E. Bullen's presidential address to the International Association of Seismology and the Physics of the Interior of the Earth at Toronto in 1957 had the title 'Seismology in our Atomic Age'. He pointed out that atomic explosions had far greater energy than the chemical explosions it is possible to use, and that they send waves deep into the interior of the Earth. Some atomic explosions have been recorded by seismographs, but there has been a reluctance by the authorities concerned to give prior information about the exact location and time of the explosions. Though this has reduced the value of these explosions for seismological purposes, a few important results have been obtained, results that seemingly could not be derived from earthquake observations. There is no doubt that if an opportunity arose to record atomic explosions, by many seismographs placed at suitable distances from the source, information would be obtained that would help us to solve the problems that now confront us. We are here, as Bullen said, in a tantalizing position, for the tools we so much need exist, but they are not very likely to be placed in our hands. With ever-increasing fear of the perilous effect of atomic explosions, seismology can scarcely hope for any to be organized for its special purposes. However, if the intention to explode bombs for other purposes is made known beforehand and the location and time are communicated, as has been the case in some recent instances, it should be possible for seismologists to make some use of them.

It is also well to remember that great masses of earthquake data are as yet unreduced and that, skilfully handled, they may yield fruitful results. New methods are also forthcoming in earthquake studies. The surface waves, not dealt with here, spread over the surface of the Earth, but they penetrate to some depth below it; in large earthquakes they may penetrate to considerable depth. The intense study of surface waves carried out in recent years, especially at the Lamont Geological Observatory, has provided a new approach to the exploration of the crust and the upper mantle.

While seismology teaches us a great deal about the interior of the Earth there is certainly very much more we should like to know. If we ask what are the materials inside the Earth, in what state they are, what is their density, and so on, seismology alone does not supply the answer. We have to look to other branches of geophysics and to other sciences such as geology, the physics and chemistry of the Earth's interior, and also to astronomy for additional information. Much attention has been given to pertinent questions in recent years, but the results are, in part, highly controversial.

Important results on the density variation throughout the Earth were obtained by K. E. Bullen. The velocities of the seismic P and S waves depend on the density of the transmitting material and on the elasticity as characterized by the rigidity and the incompressibility. These three quantities cannot be derived from the two velocities, but estimates can be arrived at when information from various other sources is taken into account. Bullen finds that the density increases in the mantle from about 3·3 g/cm^3 just below the Mohorovičić discontinuity to about 5·5 g/cm^3 at the bottom of the mantle. It then jumps to about 9·5 g/cm^3 and increases to 11·5 g/cm^3 at the bottom of the outer core. In the inner core there is a strong increase. The rigidity that represents the resistance to shearing stress increases in the mantle, until at the bottom it is nearly four times that of ordinary steel. In the outer core the rigidity is quite small, and this is what we mean when we say that the core is fluid. On the other hand, the incompressibility or the

resistance to pressure does not change materially at the boundary of the core. The pressure when evaluated was found to have reached about 1⅓ million atmospheres at the bottom of the mantle and about 4 million atmospheres at the centre of the Earth. Following a long line of argument, Bullen arrives at the conclusion that the inner core is likely to be solid.

The composition of the continental crust varies a great deal from one region to another. Granite is one of its main constituents, whereas this material is absent under the deep oceans, where the crust is much thinner. The upper mantle is believed to consist of ultrabasic rock such as olivine. A transition is likely to take place, perhaps from one form of olivine to another, in the region where the seismic velocities increase more strongly than elsewhere, this region beginning at a depth of a few hundred kilometres. It has for a long time been believed that the core consists of iron and nickel, but recent investigations have led to the conclusion that the outer core possibly consists of material not much different from that of the mantle but transformed under the prevailing high pressure. The inner core is still believed to consist chiefly of iron and nickel.

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Book reviews

OPERATIONAL RESEARCH

Proceedings of the First International Conference on Operational Research, Oxford, 1957, *edited by M. Davies, R. T. Eddison, and T. Page. Pp. viii+526. The English Universities Press Ltd, London.* 1958. 50*s. net.*

Operational research is now generally regarded as sufficiently important and extensive to be looked upon as a subject existing in its own right. It has its own methods and fields of application, the former including some new branches of applied mathematics.

The first international conference on the subject was attended by 250 delegates from 21 countries. About 28 papers were presented, covering the functions and philosophy of operational research and the methods and applications. Some of the papers, such as that by P. Naor on machine interference and that by T. C. Koopmans on water storage, show the high degree of sophistication reached in the mathematical treatment; others, such as that by J. Stringer and K. B. Haley on a large-scale transportation problem, indicate a delicate blending of mathematical formulation and numerical analysis, including the use of a special analogue computer. The paper by J. C. R. Clapham and H. D. Dunn on communication in collieries is a very good example of the highly practical type of operational research, carried out in this case by the National Coal Board. Another paper of this type is that by J. R. Manning on tolerances in fitting shoes.

Accounts are given of the state of operational research (in 1957) in 16 countries. These reveal that it is now conducted on a world-wide scale. No country which seeks efficiency can afford to neglect operational research.

L. S. GODDARD

PAPER CHROMATOGRAPHY

Chromatographic Techniques: Clinical and Biochemical Applications, *edited by I. Smith. Pp. xiii+309. William Heinemann Ltd, London.* 1958. 45*s. net.*

This book deals almost entirely with the techniques of paper chromatography. The title might therefore be open to criticism, suggesting as it does a wider approach to the subject than in fact is presented. No reservations, however, need be made about the contents. Under the editorship of Dr Smith, who himself makes several important contributions, nine specialists deal with the techniques and applications of paper chromatography in their particular fields. In the chapters dealing with amino-compounds, sugars, phenolic acids, and steroids there are, in addition, separate sections dealing with clinical interpretations. There is a final chapter of model experiments for students. This is essentially a practical book and, based as it is on the wide experience of Dr Smith and his co-authors, it will be invaluable to the laboratory worker wishing to apply paper chromatography to his problems for the first time. The detailed practical instructions given will often have been sought in vain in the original literature, as pressure on space seldom permits authors to give more than the bare outline of techniques. The more experienced worker will find much unpublished information on reagents and solvents, together with complete details for their use. The bibliography is sufficiently detailed to enable those wishing to obtain a broader view of chromatography to do so. A. J. WOIWOD

PRACTICAL ORGANIC CHEMISTRY

Elementary Practical Organic Chemistry, *by A. I. Vogel. Pp. xxviii+890. Longmans, Green & Co. Ltd, London.* 1958. 45*s. net.*

This volume consists of three parts, each of which has already been published separately. Part I is a manual of preparative organic chemistry using small quantities (1–25 g) of organic chemicals and employing small-scale apparatus, some of which has been specially designed by the author. Part II deals with qualitative analysis and includes tables of derivatives which are much more comprehensive than is usual in elementary textbooks. Part III describes methods of quantitative organic analysis, mainly based on the determination of functional groups by a variety of old and new methods; it includes the determination of nitrogen, halogens, and sulphur. For many students Part III will be largely or wholly unnecessary and its inclusion in an elementary textbook is of debatable value, but for those who need all three parts the triad represents a saving of 18s.

The whole book is excellently produced and very lucidly written, as well as being illustrated with a large number of line drawings. All the procedures have been tested in the author's laboratory and are described in complete detail. Whether purchased singly or together as in the present volume, all three parts can be strongly recommended. J. F. W. McOMIE

ORGANIC CHEMISTRY

Lehrbuch der organischen Chemie (*fifth edition*), *by H. Beyer. Pp. xvi+690. S. Hirzel Verlag, Leipzig.* 1958. *DM* 22.50 *net.*

This is a partly revised, but not enlarged, version of the 3rd/4th edition (1955). The whole of organic chemistry is dealt with in 647 pages.

After a 29-page introduction on purification, analysis, and the theory of chemical bonding, 268 pages are devoted to aliphatic chemistry, 8 to cycloparaffins, 140 to aromatic compounds, 41 to hydroaromatics, terpenes and steroids, 114 to heterocyclic chemistry, and 46 to proteins and enzymes. There is a good index of 43 pages, and the references are commendably up to date, in some cases to late 1957.

The discussion of reaction mechanisms is begun early and continued throughout the book; the symbols used follow English practice fairly closely. Petroleum, plastics, stereochemistry, coenzymes, the citric acid cycle, terpenes, steroids, and alkaloids are briefly but competently dealt with. Only four pages are given to carotenoids—discussion of degradations, syntheses, and even colour of the important compounds being omitted. There is a confusing lack of uniformity in the formulae of ring compounds: to note only one example, the carbon atoms are omitted from the naphthaquinone formulae on page 431, but anthraquinone derivatives (pages 436–441) have exaggerated C=O groups placed with the C well outside the ring.

The general effect of the book is to give the reader a fascinating picture of the range of organic chemistry, though the treatment of most topics must be brief in a volume of this size. The printing is excellent, and the paper is a great improvement on that used in the previous edition. One result is that the thickness of the volume has been reduced to $1\frac{3}{4}$ in. As the author's style is clear, this book should provide honours students with stimulating views of the subject. J. C. SMITH

ELECTRONIC THEORIES OF ORGANIC CHEMISTRY

An Introduction to Electronic Theories of Organic Chemistry, *by G. I. Brown. Pp. viii+209. Longmans, Green & Co. Ltd, London.* 1958. 15*s. net.*

Within a comparatively short space of time the nature of organic chemistry has undergone a revolutionary change, owing to the application of electronic theories to problems of constitution and reaction. So fundamental is the change that even students of the elements of organic chemistry find it necessary to acquire at least a qualitative familiarity with the principal features of the theories concerned. Mr Brown's book is a notably successful effort to provide this information in an easily intelligible way.

After a concise, and very useful historical introduction to the development of ideas on the general structure of organic compounds, a chapter is devoted to the nature of the atom; this is perhaps unduly compressed and would serve better as a recapitulation for more experienced students than as pabulum for the beginner. Such criticism does not apply to the rest of the book, which takes the reader by logical stages from the formation of interatomic bonds and the nature of covalency to the structure of benzene, substitution in the benzene ring, and reaction mechanisms. Hydrogen bonding receives a short but sufficient chapter, in which the effect of this bonding upon the basic strength and solubilities of amines, and upon association and chelation, is described and explained. The book concludes with a bibliography and a full index. It should be of value not only to science specialists at school but to undergraduates and to those mature organic chemists who have occasion for a rapid survey of electronic theory in relation to aspects of their chosen field. E. J. HOLMYARD

MODERN ORGANIC CHEMISTRY

A Modern Approach to Organic Chemistry, *by J. Packer and J. Vaughan. Pp. x+973. Oxford University Press, London.* 1958. 84*s. net.*

The study of reaction mechanisms in the field of organic chemistry over the past thirty years has proved so fruitful that as a result our understanding and practice of the subject have been transformed. We have been slow in Britain to incorporate into our undergraduate courses the principles that have resulted, and this is paralleled by a dearth of elementary textbooks which feature mechanistic concepts as an integral part of exposition. The authors of this book have set out to remedy this situation and within their self-imposed limits have made a useful contribution. Theory is introduced (albeit with a distinct English emphasis) as the need for its understanding arises. Thus structural theory in terms of atomic and molecular orbitals is presented in an introductory chapter; the concept of resonance first appears in the discussion of conjugated di-olefines; homolysis and heterolysis are defined before the addition reactions of alkenes; substitution and elimination reactions fit into the chapter on alkyl halides. Wherever possible the authors have included reaction mechanisms; where these are merely speculative this is generally indicated. Just over one-half of the book is devoted to aliphatic, the remainder to aromatic and heterocyclic chemistry (only 45 pages to the last). For a book aiming to present 'a modern approach to organic chemistry' there are notable omissions: steric factors in reaction mechanisms and conformational analysis receive only the briefest mention; natural products, including proteins, vitamins, alkaloids, steroids, and terpenoids, and the concept of biogenesis are omitted entirely. The authors have taken a somewhat limited

view of their field, and it will not be surprising if at its price this book does not commend itself to students. It should nevertheless do something to invigorate our teaching methods, and in this context the authors merit our gratitude for taking a step in the right direction.

The type and layout are on the whole admirable. The completely indiscriminate use of the cyclohexane and Kekulé symbols to represent aromatic rings is, however, wholly deplorable. K. H. OVERTON

THE IONOSPHERE

The Ionosphere, *by K. Rawer. Pp.* 202. *Crosby Lockwood & Son Ltd, London.* 1958. 42*s. net.*

This book, written five years ago, will already be known in its German edition to many workers on the ionosphere. An English translation is very welcome.

The subject is introduced by a description of the method of echo sounding and of the propagation of radio waves in an ionized medium. Other methods of investigating the upper atmosphere are described, including the use of rockets, but not, of course, artificial satellites. Theories of the formation of the ionized layers are explained and the regular and irregular changes of the ionosphere are discussed. A final chapter deals with the application of the results to practical radio communication.

The book will be most useful to research workers and to radio engineers interested in the more scientific aspects of research on the upper atmosphere. The extensive bibliography is very valuable. The general reader will not find the book easy to read, though some sections are of general interest.

It is unfortunate that the clarity of the author's writing has not been preserved in the English translation. The text gives the impression of having been translated word for word with little attempt to use idiomatic English. Even recognized technical terms are not always correctly translated. As an example, the term 'space wave' is used where 'sky wave' would have been correct. Experienced workers will no doubt be able to guess the meaning in most cases. A student new to the subject would, however, pick up some very unfamiliar terms if he confined his reading to this book. There are also a number of misprints.

B. H. BRIGGS

EVOLUTION

The Evolution of Development, *by J. T. Bonner. Pp. vii* + 103. *Cambridge University Press, London.* 1958. 17*s.* 6*d. net.*

In the smallest unicellular organisms the young and adult differ only in size; there are no embryological processes as we know them in higher animals. These processes have apparently evolved independently in many different lines as multicellular organisms appeared. The existing simple multicellular forms show various types of development, and from study of these the author tries to deduce the advantage for survival that is provided by having adults that differ from the young. For example, the slime moulds have no processes of meiosis and fertilization, but their genetic systems allow, in their own special way, for mutation and dispersal of the variants. Evolutionary adaptational changes can thus proceed, but without any of the advantages of recombination that are provided by sexual processes. The mechanism of 'development' in these organisms does not follow cleavage of a fertilized egg, but results from the coming together of numerous separate amoeboid cells. Thus the race achieves the advantages both of reproduction by division into small bodies and of large sizes and differentiated parts in the adult stage.

The author pursues most ingeniously the idea that what is involved is a 'package of variations' and that in order for these to be effectively displayed, a process of development involving proper spacing of the parts under the control of a communication system of polarities and gradients is necessary.

With this theme many examples of reproductive processes in lower organisms are discussed. Finally, there is a sudden and surprising jump to the subject of communication between higher animals as shown by the ethological school of Tinbergen and Lorenz. It is not clear why the author should have chosen to call attention to these rather than to the many other examples of communication that are involved in the physiology and behaviour of higher organisms. The various types of communication can only be made to illuminate each other, however, by the use of a common and exact terminology, such as that of information theory, which, quaintly enough, is not even mentioned in the book. J. Z. YOUNG

PROTEIN STRUCTURE

Symposium on Protein Structure, *edited by A. Neuberger. Pp.* 351. *Methuen & Co. Ltd, London; John Wiley & Sons Inc., New York.* 1958. 45*s. net.*

Those who attended the I.U.P.A.C. Symposium on Protein Structure held in Paris in 1957 will recognize in this book a faithful record, not only of the proceedings, but of the spirit of this conference. The contributions, though necessarily limited in number, cover a wide field, yet reflect a theme which has been admirably brought out by Professor Neuberger's editing.

Discussions of individual proteins in this volume indicate acceptance of the concepts of primary, secondary, and tertiary structure as aids to elucidating their nature. The contributions of physical and organic chemists appear here in fruitful juxtaposition. Thus determination of the amino-acid sequence in enzymes (such as ribonuclease, discussed herein) seems a prerequisite for investigations of the chemistry of the active centre; the spatial configuration of the protein must also play a vital role, and here such methods as deuterium exchange and X-ray crystallography may provide an answer.

Discussion of such methods is provided in this book, but perhaps its main value is in the indications it gives of future progress in the field. 'Active fragments' of papain, pepsin, enolase, and bovine serum albumin are mentioned. 'Common amino-acid sequences' in the pituitary hormones and pancreatic proteinases are discussed. Progress in X-ray crystallography and in immunology is indicated, and papers on haemoglobin and tobacco mosaic virus suggest that protein microstructure may become, as Fraenkel-Conrat suggests, 'the Rosetta Stone of biochemical genetics'.

The paper, type, and diagrams are of unusually high quality for this type of book at this price. B. S. HARTLEY

ENZYMES

Enzymes, *by M. Dixon and E. C. Webb. Pp. xxxiii* + 782. *Longmans, Green & Co. Ltd, London.* 1958. 90*s. net.*

This is an encyclopaedic volume. The authors tabulate 659 enzyme reactions and produce photographs of all but fifteen of the enzymes that have been crystallized. This sets the tone for a systematic discussion and tabulation of most of the properties of the enzymes that any research worker may wish to look up. Ample references are made to

original papers from which all this wealth of information has been extracted. Experimental techniques are, however, barely discussed, though some methods for enzyme purification and rate measurements are briefly summarized. Incidentally, it does seem odd to include some elementary kinetic algebra in the short chapter on enzyme techniques rather than in the chapter on enzyme kinetics. This has, however, obviously been done intentionally, and most of the criticisms which working enzymologists may level against one chapter or another are matters of opinion about the order or priority of space given to various subjects. The authors would not be human if there were not some errors and misleading statements as well as a little too much special pleading for some not very important hypotheses; but in general, on properties of isolated enzymes, the book can be used as a reliable guide. All biochemists must be grateful to the authors for producing such a comprehensive 'one-volume' treatise.

H. GUTFREUND

ENZYME CHEMISTRY

The Chemical Kinetics of Enzyme Action, *by K. J. Laidler. Pp. vi+419. Clarendon Press, Oxford.* 1958. 60*s. net.*

The publishers state on the dust-jacket that this book has been written both for biologists who are interested in enzyme mechanisms and for physical chemists who are interested in applying their methods to biological systems. It is the reviewer's opinion that the usefulness of this volume is much more restricted. It should really be called 'Kinetics for Biochemists' or 'Kinetics for Enzymologists', and as such should serve a good purpose. It is very doubtful whether a physical chemist wanting to apply his methods and ideas to biological problems would be well advised to use this book as a guide. It is clear that the author is well versed in the manipulation of kinetic equations and has a lucid way of presenting them, and it would perhaps have been better if Professor Laidler had restricted himself to this and, possibly, expanded his treatment to multi-enzyme systems and steady-state processes. Much of what he has to say about the biochemistry of enzymes and their reactions is presented better in other books, and many of the numerical data quoted are quite wrong.

Judging from the dates of the references quoted, the manuscript was completed two years before the book was published. That is a very long delay. The additional references to more recent work, given in an appendix, hardly make up for this. One would also have expected more careful proofreading of a book which has taken so long to produce. A change of the nomenclature for the Michaelis constant is not likely to be well received, and the inconsistency in nomenclature in this volume is unforgivable.

In spite of such criticisms, the book will prove valuable for reference.

H. GUTFREUND

TREE PHYSIOLOGY

The Physiology of Forest Trees, *edited by K. V. Thimann, assisted by W. B. Critchfield and M. H. Zimmermann. Pp. xvi+678. The Ronald Press Co., New York.* 1958. $12 *net.*

The Maria Moors Cabot Foundation is to be congratulated for arranging the symposium that brought together, at Harvard Forest, physiologists actively interested in work with forest trees. This book gives an account of the symposium.

As might be expected, the formal papers and discussion on many of the topics emphasized outstanding problems and pointed to the relevance of recent physiological work to scientific forestry. The book is divided into nine sections: water relations, photosynthesis, biochemistry, mineral nutrition, phloem transport, root growth, general growth phenomena, photoperiodism and thermoperiodism, and reproduction. Each section consists of a series of papers, some of which are reviews and others accounts of the methods or the results of particular studies. The most laudable characteristic of the symposium is the emphasis on the physiology of whole plants, for although much of the experimental work must be done on seedlings or parts of trees, each of the contributors attempted to assess the extent to which the results applied to the whole tree.

The book, which has been well edited and indexed, should be of interest both to plant physiologists and to working foresters. Some of the sections, for example those on photosynthesis and growth phenomena, review physiological knowledge so relevant to forestry that one wonders whether more frequent symposia or reviews of a similar nature might not prove valuable.

J. L. HARLEY

MOLLUSCAN MORPHOGENESIS

Morphogenesis: The Analysis of Molluscan Development, *by C. P. Raven. Pp. xii+311. Pergamon Press Ltd, London.* 1958. 70*s. net.*

In this book, which owes much to his own researches on development in the water snail *Limnaea stagnalis*, Professor Raven has brought together what is known of development in the Mollusca and shown how modern experimental studies are revealing the directive forces and the chemical interactions responsible for the sequence of structural change. The result is a much better balanced book than one concerned solely with experimental and chemical embryology; increase in depth more than offsets loss in breadth.

Dealing first with structure at all levels of complexity and then with what the experimentalists have achieved of causal analysis, Professor Raven starts with oogenesis, followed by chapters on maturation and fertilization, on cleavage, on gastrulation, on embryogenesis and on organogenesis. All are clearly presented and, especially in the earlier chapters, admirably illustrated. The comprehensive list of references gives, one is glad to note, full titles for all papers.

What matters in development are the genes in the nucleus, the particular assortment of material in the cytoplasm, and the effect of a cortical field considered to possess not only polarity but dorsoventral and transverse organization. Fascinating fields for further research unfold themselves. Workers on Mollusca, embryologists, general zoologists—all will profit from this book.

C. M. YONGE

ECOLOGY

Spiders, Scorpions, Centipedes and Mites. The Ecology and Natural History of Woodlice, 'Myriapods' and Arachnids, *by J. L. Cloudsley-Thompson. Pp. xiv+228. Pergamon Press Ltd, London.* 1958. 50*s. net.*

It is the subtitle rather than the title itself that reveals the aim of this excellent book. It is, in fact, concerned with the ecology—the life and the environment of—these animals and on this the author is authoritative: he has studied the animals he writes about, and for ecology this is of prime importance. The chapters are each concerned with one zoological group and are arranged in the same way, dealing with classification, distribution, method of movement, nutrition, vital cycles, and

reproduction, all excellently illustrated with photographs and drawings. A rich collection of personal observations and acute comments conveyed in clear, concise prose deals with several major problems, notably of water exchange, and reveal the author as a thoughtful student of many facets of animal life. Even the specialist will find this book full of new information, and it should be read by anyone interested in animal life and adaptation. A systematic index and a glossary help the reader with the small number of necessary technical terms. M. VACHON

CARCINOGENESIS

British Medical Bulletin, Vol. XIV, No. 2, Causation of Cancer. *Pp.* 73–196. *The British Council, London.* 1958. 25*s. net.*

This number of B.M.B. on 'Causation of Cancer' comprises 21 reviews by 27 investigators from 16 centres in Britain and the Commonwealth. Appearing eleven years after a similar symposium in the same journal, it portrays the progress made during this period of rapid advances in the study of carcinogenesis.

Within the limitations of some 150 pages an interpretative rather than exhaustive analysis was clearly aimed at, with scant reference to work before 1947, and a selection of the most significant subsequent publications. While such a selective approach tends to permit personal bias, a commendable degree of objectivity was nevertheless maintained in most of the reviews. Furthermore, the interpretative treatment, with cautious speculations, helps to show the logical trend and purposefulness in each field—a quality not often detectable in more comprehensive reviews. This approach is a useful corrective to the dubious notion that science is best served by 'letting the facts speak for themselves'.

The choice of titles gives a clue to the fields in which progress has been most noteworthy. Thus, of the 21 reviews five are devoted to radiation—two in connection with leukaemogenesis; two deal with bladder carcinogenesis and another with the related subject of aromatic amines; two with co-carcinogenesis; one with endocrine carcinogenesis; and one with dynamic aspects of chemical carcinogenesis. Other reviews that represent progress of a less dramatic kind deal with the carcinogenicity of petroleum oil fractions, occupational carcinogenesis, experimental liver carcinogenesis, exogenous factors in lung tumours, and cholesterol carcinogenesis. The review on avian carcinogenesis does not record much recent progress; the one on the immunological basis of carcinogenesis is highly speculative; that on biological examination of chemical carcinogens has a decidedly practical slant. The introductory review on chemical carcinogens and their mode of action is broad in its conception, with perhaps an over-emphasis on chemical mechanisms.

The virtual absence of any discussion on viruses is rather surprising in a symposium on causation of cancer. Actually the title of the symposium is misleading, since the reviews concern themselves only with carcinogenesis.

This issue is dedicated to the memory of the late Sir Ernest Kennaway, who, more than any other, established the investigation of carcinogenesis on a truly scientific footing. I. BERENBLUM

INFECTIOUS DISEASES

Die Infektionskrankheiten des Menschen und ihre Erreger, *Vols. I and II, edited by A. Grumbach and W. Kikuth. Pp.* xl+840; 841–1702. *Georg Thieme Verlag, Stuttgart.* 1958. *DM* 198 *net.*

The authors have designed these volumes as a link between clinicians and biologists, to give clinicians some idea of the scope of modern developments in microbiology and parasitology and to give biologists some idea of the clinical picture. It is primarily a textbook of microbiology.

Basic general principles of the relationship between host and parasite, immunity, epidemiology, chemotherapy, and the morphology and physiology of bacteria, rickettsia, viruses, fungi, protozoa, and helminths are given in the general section of some 400 pages.

The special section deals with the various pathogenic micro-organisms individually. A brief note on the clinical condition caused by the parasite is followed by an extensive description of the morphology, physiology and biochemistry of the organism. A critical discussion of pathogenesis, epidemiology, diagnosis, specific therapy, and prophylaxis completes the picture. Extensive references to the literature, with titles of articles, are given in each section. These are up to date and cover English, American, and European publications. It is not a laboratory manual, and there are no photographic illustrations. It is, however, a valuable reference work in which the editors have succeeded in keeping a consistently high standard of clear expression and critical judgment in chapters by seventeen different authors. R. L. VOLLUM

HISTORY OF MAGIC AND SCIENCE

A History of Magic and Experimental Science, *Vols. VII and VIII:* The Seventeenth Century, *by Lynn Thorndike. Pp.* x+695 *and* viii+808. *Columbia University Press, New York; Oxford University Press, London.* 1958. 80*s. net per volume.*

Some thirty-five years ago the present writer had the privilege of reviewing the first two volumes of 'A History of Magic and Experimental Science'. It is therefore with particular pleasure that he welcomes this opportunity of congratulating Professor Lynn Thorndike upon the successful completion of his great work: the fruit of over half a century of writing and research.

All historians of science are familiar with the earlier volumes of this 'History', and rightly regard them as indispensable to the serious student of the subject. The concluding volumes merit the same high respect. As before, they are characterized by the author's astonishingly wide and deep knowledge of original sources, and one is inevitably reminded of Goldsmith's schoolmaster: 'and still the wonder grew, That one small head could carry all he knew'. But Thorndike's erudition sits lightly on his shoulders; his style is easy, and the narrative flows smoothly and compellingly. Comments, criticisms, and judgments are refreshingly individual and often enlivened by a dry, scholarly humour—as when it is suggested that Boyle's works appear so frequently in secondhand book catalogues either because no one will buy them or because those who do so find them unreadable and return them to the market.

By the seventeenth century the age of modern science was well under way. Yet it is easy to overestimate the extent and depth of the rational, scientific thought of the period: the occult arts and pseudo-sciences still flourished, often among men who made genuine scientific advances of the first order. Newton, for instance, was 'an unbridled addict' of alchemy; Boyle thought that tonsillitis could be cured by strangling a viper with 'divers sorts of threads' and then tying the threads about the neck of the patient; and Descartes believed that the wounds of a corpse bled at the

approach of the murderer. To get an accurate picture of seventeenth-century science such aberrations must necessarily be taken into consideration. Not the least merit of Thorndike's work is that it helps us to view the progress of human thought and discovery in proper perspective. E. J. HOLMYARD

BIOGRAPHY

D'Arcy Wentworth Thompson, the Scholar-naturalist, 1860–1948, *by Ruth D'Arcy Thompson. Pp. xi+244. Oxford University Press, London.* 1958. 25*s. net.*

At a time like this, when the problems of how to combat specialization and how to blend the humanities with science and technology are perennial subjects for academic pamphleteering, it is important to recollect that only ten years ago a man died who solved these problems in his own personality. He was D'Arcy Thompson, author of 'Growth and Form' (one of the few scientific books assured of immortality) and for over sixty years professor in Dundee and St Andrews. His daughter Ruth has put scientists in her debt by writing a sensitive and frank and altogether delightful life of her father. She succeeds remarkably in bringing to life his buoyant and boisterous personality, the restless power of his mind, and his overflowing kindness.

For D'Arcy Thompson there were no curtains of the mind between different subjects. He graduated in science. His Cambridge doctorate was in classics. His most important publications were in mathematics applied to biology. He made major contributions to the technology of the fishing industry. He was a master of the English language. Of course, he paid a price for this virtuosity. He published very little of what conventional scientists call original research. It is a little ironic to read letters from his teachers and friends urging him to do research for the sake of his reputation. Fortunately he disregarded their advice, and instead made a unique contribution to humanity.

The value of this admirable book is enhanced by a brief and masterly essay on D'Arcy Thompson's scientific work by Professor P. B. Medawar, whose own command of English would have earned D'Arcy Thompson's approval.

E. ASHBY

MEDICINE AT SEA

Medicine and the Navy 1200–1900, *by J. J. Keevil. Vol. II,* 1649–1714. *Pp. xii +332. E. & S. Livingstone Ltd, Edinburgh.* 1958. 40*s. net.*

The first volume of this work was reviewed in this journal in January 1958 (XVII, 53). The speedy appearance of the second volume, while most welcome in itself, is overshadowed by the fact that the author died, at a comparatively early age, before its publication. Surgeon Commander Keevil's knowledge of his subject was unrivalled, and it is much to be hoped that he left sufficient material for the work to be completed by another hand.

The present volume, covering the period of the Commonwealth, the Protectorate, and the early Stuarts, describes how the medical service of the Navy gradually developed into a corporate organization serving the specialized needs of medicine and surgery afloat. The process was a slow one and suffered many vicissitudes; sea-surgeons were badly paid, had no security of tenure, and alone among subordinate naval officers were not appointed by warrant. That matters eventually improved was largely due to the sheer force of circumstances. The almost continuous wars of the period brought appalling casualties, and the authorities were driven by necessity to make better and more ample provision for the sick and wounded. Sickness caused more deaths than did enemy action; thus in 1693 Sir Francis Wheler's naval expedition to Barbados lost 1300 sailors out of 2100 and 1800 soldiers out of 2400 from sickness, mainly from yellow fever.

Faced by such calamities, successive governments of the period slowly came to realize the importance of adequate medical staff, accommodation, equipment, and hospital ships for the Navy, and Commander Keevil tells the story of this belated and chequered amelioration. This volume, like the first, contains much of interest to scientists; it is admirably written, fully documented, and attractively illustrated.

E. J. HOLMYARD

A CENTURY OF FRENCH INVENTIONS

Brevets d'invention français, 1791–1902: Un siècle de progrès technique. *Pp.* 321. *Ministère de l'Industrie et du Commerce, Paris.* 1958.

This book is a guide to and catalogue of an exhibition opened at the *Institut National de la Propriété Industrielle*, Paris. The purpose of the exhibition is to illustrate the development of techniques during the course of the nineteenth century by descriptions given in patent grants. The number of such grants being very large, rigorous selection was inevitable, and about two hundred were finally chosen for exhibition. These come from a wide range of activities, including agriculture, foodstuffs, locomotion, textiles, steam and other engines, machine tools, building construction, public works, mines, metallurgy, firearms, telecommunication, legal metrology, electricity, ceramics and glassmaking, chemistry, heating, lighting, refrigeration, the graphic arts, photography, and music.

Besides a preface by Marcel Plaisant and a foreword by Guillaume Finniss there is an excellent general introduction by Maurice Daumas, of the *Conservatoire National des Arts et Métiers.* There are also short introductory passages to each of the various sections of the catalogue. In the exhibition, the patent documents are accompanied by relevant accessory material such as portraits, photographs, paintings, and models; these, too, are listed in the catalogue and considerably add to its interest. Among the subjects of the plates are a patent taken out by Pasteur in 1865 for a procedure relative to the conservation of wines, another (1877) by Friedel and Crafts for a method of preparing hydrocarbons, Thimonnier's sewing machine (1830), and a model of Héroult's electric furnace for the manufacture of aluminium.

The catalogue is of more than ephemeral value, and many scientists will be glad to have a copy on their shelves.

E. J. HOLMYARD

Short notices of books

(These notices are descriptive rather than critical and are designed to give a general indication of the nature and scope of the books.)

A Dictionary of Named Effects and Laws in Chemistry, Physics and Mathematics, *by D. W. G. Ballentyne and L. E. Q. Walker. Pp. v+205. Chapman and Hall Ltd, London.* 1958. 30*s. net.*

Scientists, especially those reading in a field not their own, who wish to identify a law, an effect, or a reaction associated with some particular scientist, are the intended users of this dictionary. The entries are arranged alphabetically, and historical and other background information is deliberately excluded.

The Physics of Rubber Elasticity (*second edition*), *by L. R. G. Treloar. Pp.* 342. *Oxford University Press, London.* 1958. 40*s. net.*

The main object of this book is to present the statistical theory of rubber elasticity and to show how this theory provides an explanation of the main physical properties of rubber-like materials. This edition has new material on swelling, crystallization, photoelasticity, and the phenomenological theory of large elastic deformations, including the application of the latter theory to engineering problems.

Tables of Interatomic Distances and Configuration in Molecules and Ions, *edited by L. E. Sutton. Pp.* 365. *The Chemical Society, London.* 1958. 42*s. net.*

A collection of results from electron diffraction studies of gases published by P. W. Allen and L. E. Sutton in 1949 was the origin of this book. It was decided that a more comprehensive work was needed rather than merely a second edition, and the book therefore contains all the useful data on interatomic distances and configuration in molecules and ions published before 1st January 1956.

The contents include a table of selected bond lengths giving the values believed to be known to ±0·02 Å or better; tables of inorganic and organic compounds, reference tables giving the literature reference and stating the method of measurement used; and a classified name index of organic compounds.

Higher Oxo Alcohols, *by L. F. Hatch. Pp. ix+120. John Wiley & Sons Inc., New York; Chapman and Hall Ltd, London.* 1958. 36*s. net.*

The oxo reaction is the reaction between an olefine, carbon monoxide and hydrogen to form a saturated aldehyde with one carbon more than the original olefine. This book reviews the patent literature on the oxo process—the complete reaction forming an alcohol from an olefine—and gives added information on the properties and utilization of the higher oxo alcohols.

Biological Laboratory Data, *by L. J. Hale. Pp. xx+132. Methuen & Co. Ltd, London; John Wiley & Sons Inc., New York.* 1958. 15*s. net.*

The aim of this book is to provide the mathematical, physical, and chemical data frequently required by the research biologist, together with a selection of recipes. The data include tables, algebraic and geometrical formulae, and information on vapour pressure, *p*H, and buffers, and recipes are given for saline media, salt water, and culture media; the histological section includes information on staining. There are references to further sources of more specialized information.

Advances in Enzymology, *Vol. XX, edited by F. F. Nord. Pp. vii+488. Interscience Publishers Inc., New York; Interscience Publishers Ltd, London.* 1958. $12.50 *net.*

There are twenty essays in this volume, on subjects which include the possible relation between optical activity and ageing, the role of imidazole in biological systems, the enzymology of the plastids, and antibiotics and plant diseases. The book includes a cumulative index to volumes I–XX, as well as separate indexes to volume XX itself.

Molluscs, *by J. E. Morton. Pp.* 232. *Hutchinson & Co. (Publishers) Ltd, London.* 1958. 10*s.* 6*d. net.*

The author of this book aims to provide an introduction to the form and functions of the *Mollusca* in the light of present-day studies. It discusses the basic structure and evolutionary pattern of the six classes of living molluscs; final chapters deal with the classification and evolutionary radiation of the Gastropoda, Lamellibranchia, and Cephalopoda. The volume is one of the Hutchinson University Library.

The Circulation of the Blood, *by William Harvey. Pp. xxiii+184. Blackwell Scientific Publications Ltd, Oxford.* 1958. 22*s.* 6*d. net.*

Two anatomical essays, addressed to Jean Riolan, jr., on the circulation of the blood, written in reply to a work of Riolan taking a modified Galenist view, are published in this book, together with nine letters by Harvey. The essays and letters are given in the original Latin, together with a slightly annotated English translation by K. J. Franklin, who has also added a short biography.

Electric Technology, U.S.S.R. *Chairman of the Editorial Board, Philip Sporn. Vol. I. Pp.* 179. *Pergamon Press, London.* 1958. *Subscription £20 p.a. for four volumes.*

The Pergamon Institute publishes this journal, which consists of selected papers from Электричество (*Elektrichestvo*), the Russian journal covering electrical engineering except for the fields of radio communication and electronics. This number contains translations of sixteen selected papers from Nos. 1–4, 1957, of *Elektrichestvo.*

Statistical Theory of Irreversible Processes, *by R. Eisenschitz. Pp. viii+83. Clarendon Press; Oxford University Press, London.* 1958, 8*s.* 6*d. net.*

This book presents previously unconnected topics in the microphysical theories of macroscopic irreversible processes as special instances of the general theory which has only recently gained a sound dynamical foundation. The assumptions of the theory are clarified and attached to the macroscopic phenomena, discarding arbitrary speculation, and mathematical deductions are supplemented by verbal reasoning. Most of the results are deduced from classical rather than quantal dynamics.

Sound pulses, *by F. G. Friedlander. Pp. xi+202. Cambridge University Press, London.* 1958. 40*s. net.*

This monograph deals with aperiodic disturbances with clearly defined fronts, using a treatment based on the theory of linear differential equations of hyperbolic type. The subjects covered include the equations of motion, wavefronts and characteristics, geometrical acoustics, and the diffraction of a pulse by wedges, spheres, and other objects.

Notes on contributors

D. J. MALAN,
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Was born in South Africa in 1905. He was educated at the University of Cape Town and at the Sorbonne, Paris. After lecturing in physics at the Universities of Cape Town and the Witwatersrand he joined the staff of the Bernard Price Institute of Geophysical Research in 1946 as a full-time research worker on atmospheric electricity. He has been associated with B. F. J. Schonland in research on lightning since 1931 and has published many papers on the subject.

W. A. SMEATON,
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Was educated at Harrow County School, Morrison's Academy, Crieff, and Imperial College, London. He graduated in chemistry in 1945, and from 1946 to 1958 taught inorganic chemistry at Northern Polytechnic, London. Since 1952 he has also carried out research in the history of science at University College, London, and he is now a research fellow in the *Institut d'Histoire des Sciences et des Techniques* of the University of Paris. He has worked mainly on French science of the late eighteenth century.

J. A. STEERS,
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Was born in 1899 at Bedford, and was educated privately and at St Catharine's College, Cambridge. He spent about two years as a schoolmaster, and in 1922 he returned to Cambridge as a student demonstrator, was elected a Fellow of St Catharine's in 1925, and later held the offices of Tutor, Dean, and President. In the university he succeeded Professor Debenham in the chair of geography in 1949. He has been particularly interested in coastal physiography in Great Britain and has also studied tropical coasts in Queensland and Jamaica. This year he is Visiting Professor at Berkeley Campus, University of California.

E. T. HALL,
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Was born in 1924 and was educated at Eton and New College, Oxford, where he graduated in chemistry in 1953. He later took his doctorate in physics at the Clarendon Laboratory, where he worked on primary and secondary X-ray fluorescence. He has been Director of the Archaeological Research Laboratory in Oxford since it was established in 1954–55. During the past four years he has directed research into the development of special techniques in X-ray, optical emission and γ-ray spectroscopy, magnetic dating, and proton magnetometry for the particular purpose of solving archaeological problems.

SIR HAROLD SPENCER JONES,
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Held the position of Astronomer Royal from 1933 to 1955. He was born in London in 1890 and was educated at Latymer Upper School, Hammersmith, and Jesus College, Cambridge. From 1923 to 1933 he held the post of His Majesty's Astronomer at the Cape of Good Hope. He was knighted in 1943. He has received the Royal Medal of the Royal Society, the Gold Medal of the Royal Astronomical Society, the Janssen Medal of the Astronomical Society of France, the Bruce Gold Medal of the Astronomical Society of the Pacific, and the Gold Medal of the British Horological Institute. He is an Honorary Fellow of Jesus College, Cambridge, a past president of the Royal Astronomical Society, of the British Astronomical Association, of the Institute of Navigation, and of the International Astronomical Union. He is president of the British Horological Institute. He is a foreign member of many national academies and an honorary member of many Dominion and foreign astronomical societies. Was Secretary General of the International Council of Scientific Unions, 1956–58.

F. C. FRASER,
D.Sc., F.L.S.,
Was born in 1903 at Dingwall, Scotland, and was educated there and at Glasgow University, where he gained the degrees of B.Sc. in 1924 and D.Sc. in 1936. After a year's post-graduate demonstrating in the Geology Department he joined the Discovery Expedition (later Discovery Investigations) and served as a zoologist successively in the Royal Research ships *William Scoresby*, *Discovery*, and *Discovery II* in expeditions to the sub-Antarctic and Antarctic concerned with biology in relation to whales. He was appointed Assistant Keeper in the Department of Zoology, British Museum (Natural History), in 1933. He is the author of papers on krill (whale food) and, in some cases jointly with P. E. Purves, on various aspects of cetacean taxonomy and anatomy, and with J. R. Norman of the book 'Giant Fishes, Whales, and Dolphins'.

P. E. PURVES
Was born in Edinburgh in 1915 and was educated at Whitley Grammar School. He was appointed to the staff of the British Museum (Natural History) in 1934 after studying natural sciences at Chelsea Polytechnic and Birkbeck College. During World War II he was commissioned in the Royal Artillery. He is the author of a number of papers on the application of plastics to museum and anatomical technology. He is the co-author with F. C. Fraser of papers on the anatomy and physiology of whales and the originator of the 'ear plug' method of age determination for the baleen whales, a method applicable to mature and immature specimens of both sexes.

I. LEHMANN,
Cand. Mag., Mag. Scient., A.R.A.S.,
Was born in Copenhagen in 1888. She took a degree (Cand. Mag.) in mathematics in 1920 and another (Mag. Scient.) in geodesy in 1928, both in the University of Copenhagen, and studied mathematics at Newnham College, Cambridge, from 1910 to 1911. From 1923 to 1927 she was an assistant to the professor of actuarial mathematics in the University of Copenhagen and an assistant to the Director of *Gradmaalingen*, Copenhagen, 1925–28. She was head of the Seismological Department of the Danish Geodetic Institute from 1928 to 1953 and as such was responsible for the operation of the seismological stations at Copenhagen, Scoresby-Sund, and Ivigtut. She has written a number of papers on seismology. She was one of the founders of the Danish Geophysical Society and its president from 1941 to 1944, and was active in the formation of the European Seismological Commission, 1951, and has been a member of it since then,